Searches for Gravitational Waves by LIGO and Virgo: Recent Results and Future Plans

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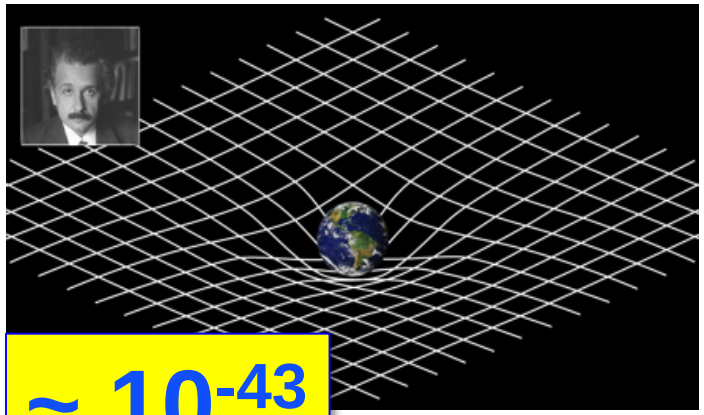
LIGO-G1900244-v1

Image Credit: Aurore Simmonet/SSU

Caltech

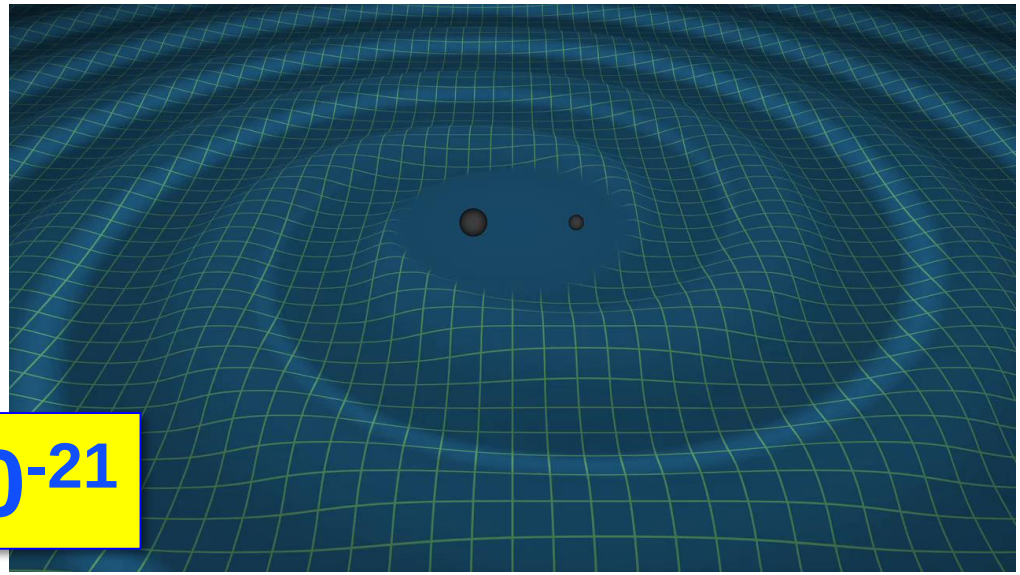
Gravitational Waves: Challenging to Detect

$$G_{mn} = \frac{8\pi G}{c^4} T_{mn}$$



~ 10^{-43}

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{mn} = 0$$



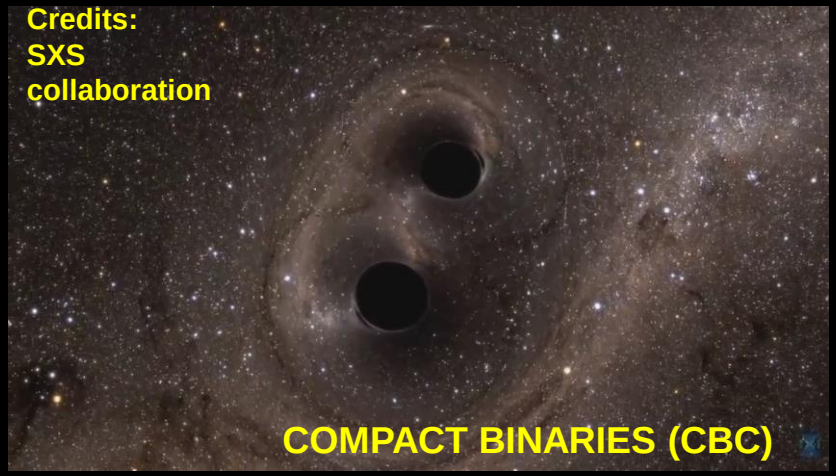
$$h_{mn} \approx \frac{1}{r} \frac{G}{c^4} \ddot{I}_{mn}$$

~ 10^{-21}

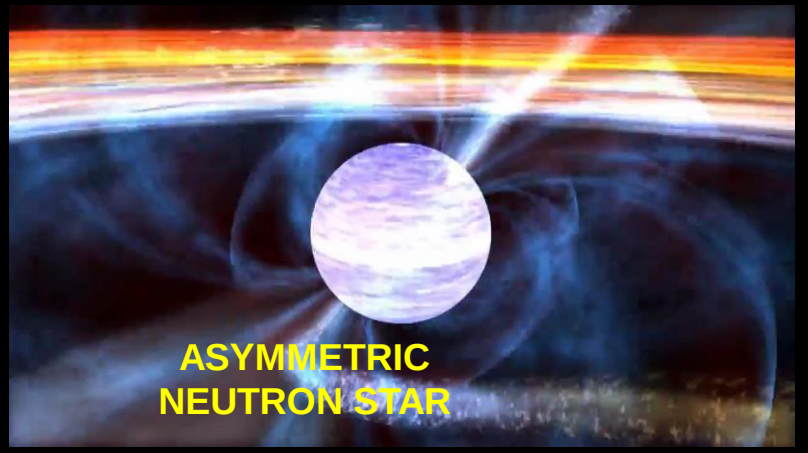
LIGO-G1900244

Gravitational Wave Targets

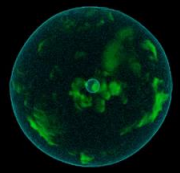
TRANSIENT



PERSISTENT



MATCHED FILTER



BURSTS
Core collapse Supernovae

UNMODELED

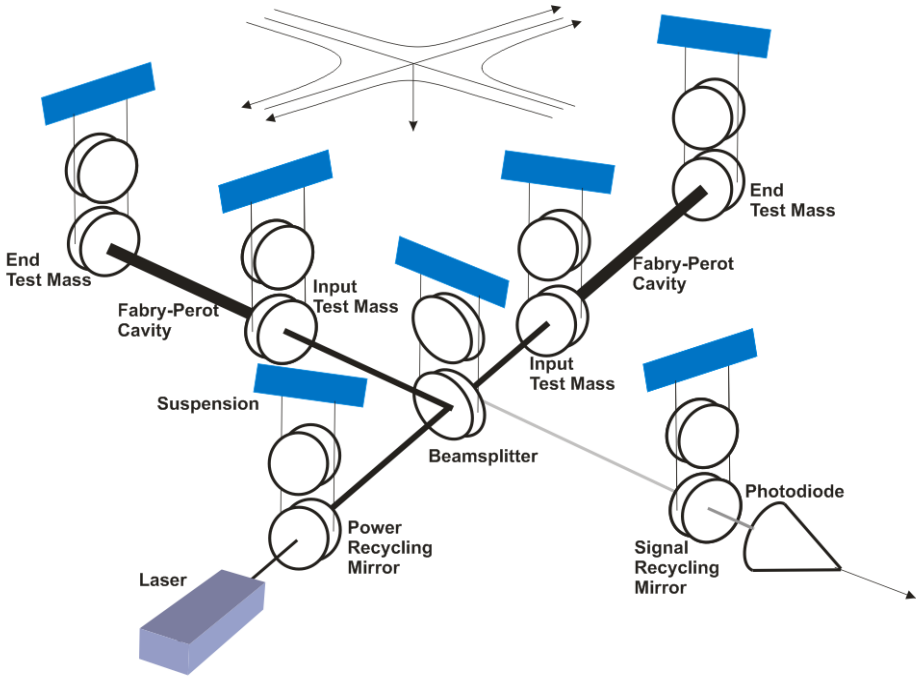
Talk Roadmap

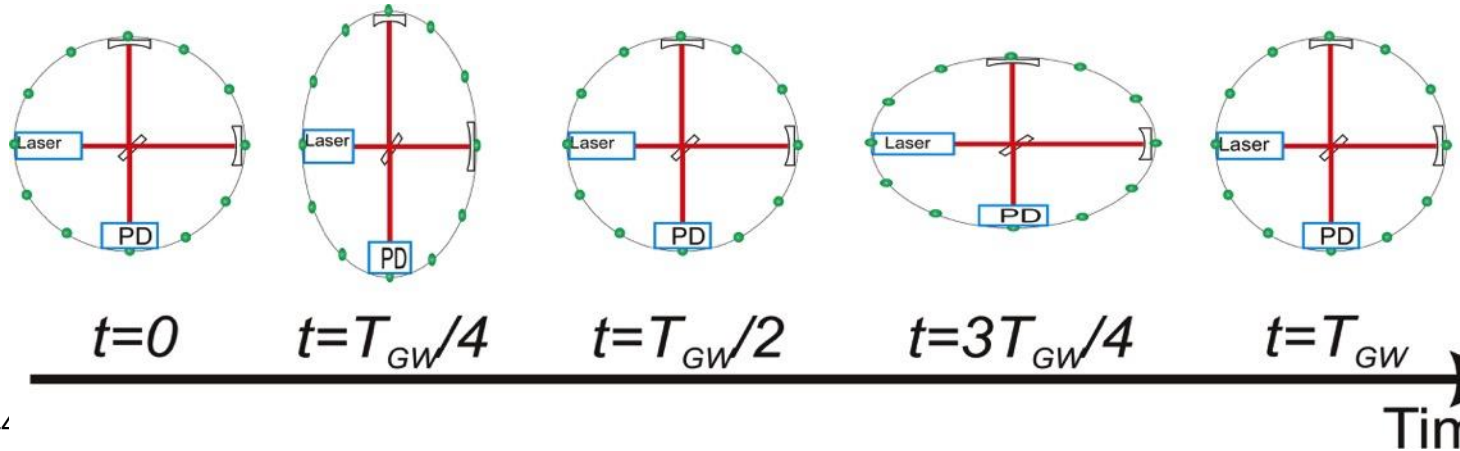
- *Gravitational Wave Detectors*
- *Recent Results*
  - » *Binary Black Hole Mergers*
  - » *Binary Neutron Star Merger GW170817*
- *Future Ground-based Gravitational-Wave Detectors*

Precision Gravitational-wave Interferometry

- LIGO uses enhanced Michelson interferometry
  - With suspended ('freely falling') mirrors
- Passing GWs stretch and compress the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - A coherent detector!
- *Sensitivity figure of merit: range to a binary neutron star (BNS) merger*

Advanced LIGO





The Global GW Detector Network

LIGO
Louisiana,
USA
4 km arms

Virgo
Cascina
Italy
3 km arms

KAGRA
Kamioka Mountain, Japan
Underground, 3 km arms
Operational in 2020

LIGO
Washington,
USA
4 km arms

LIGO-India, Hingoli, India
4 km arms
Operational in ~ 2025

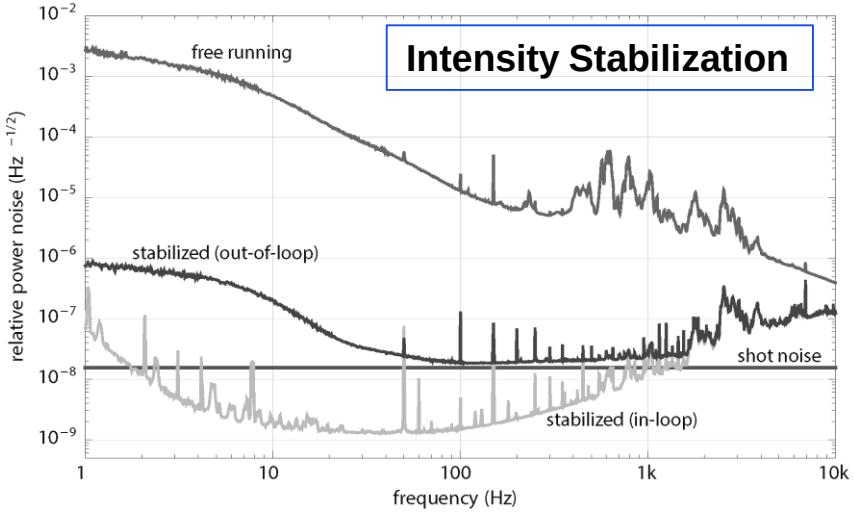
Advanced LIGO Front-end Stabilized 200W Laser

- 1064 nm laser
- Stabilized in power and frequency – using techniques developed for time references
- Uses a Nd:YAG monolithic master oscillator followed by two-stage amplification
  - 35W Nd:YVO_4 MOPA
  - 70W Nd:YVO_4 MOPA

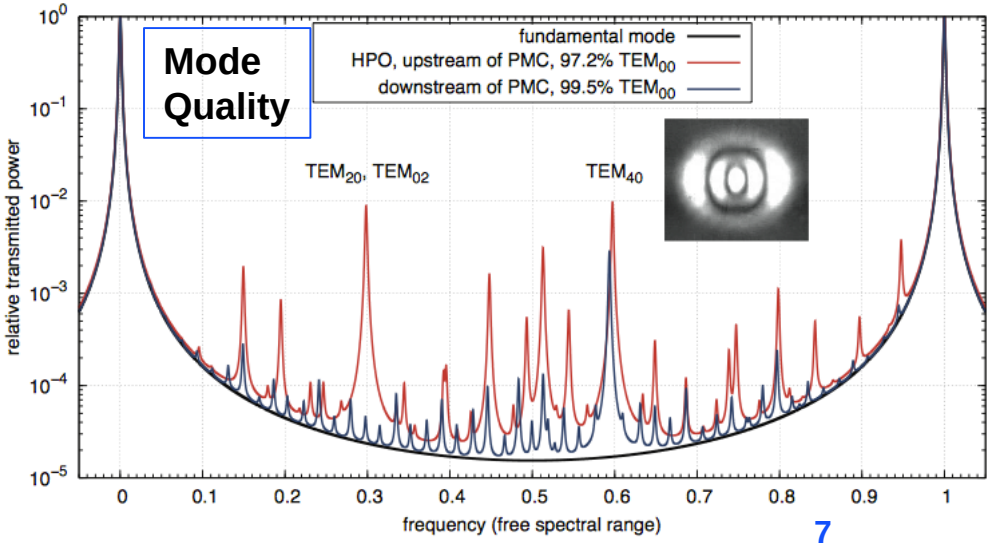
(Eventually, LIGO will deploy 200 W amplifier)

Collaboration w/
MPG Albert Einstein Institute;
Laser Zentrum Hannover

Max Planck Institute for Gravitational Physics
Albert Einstein Institute

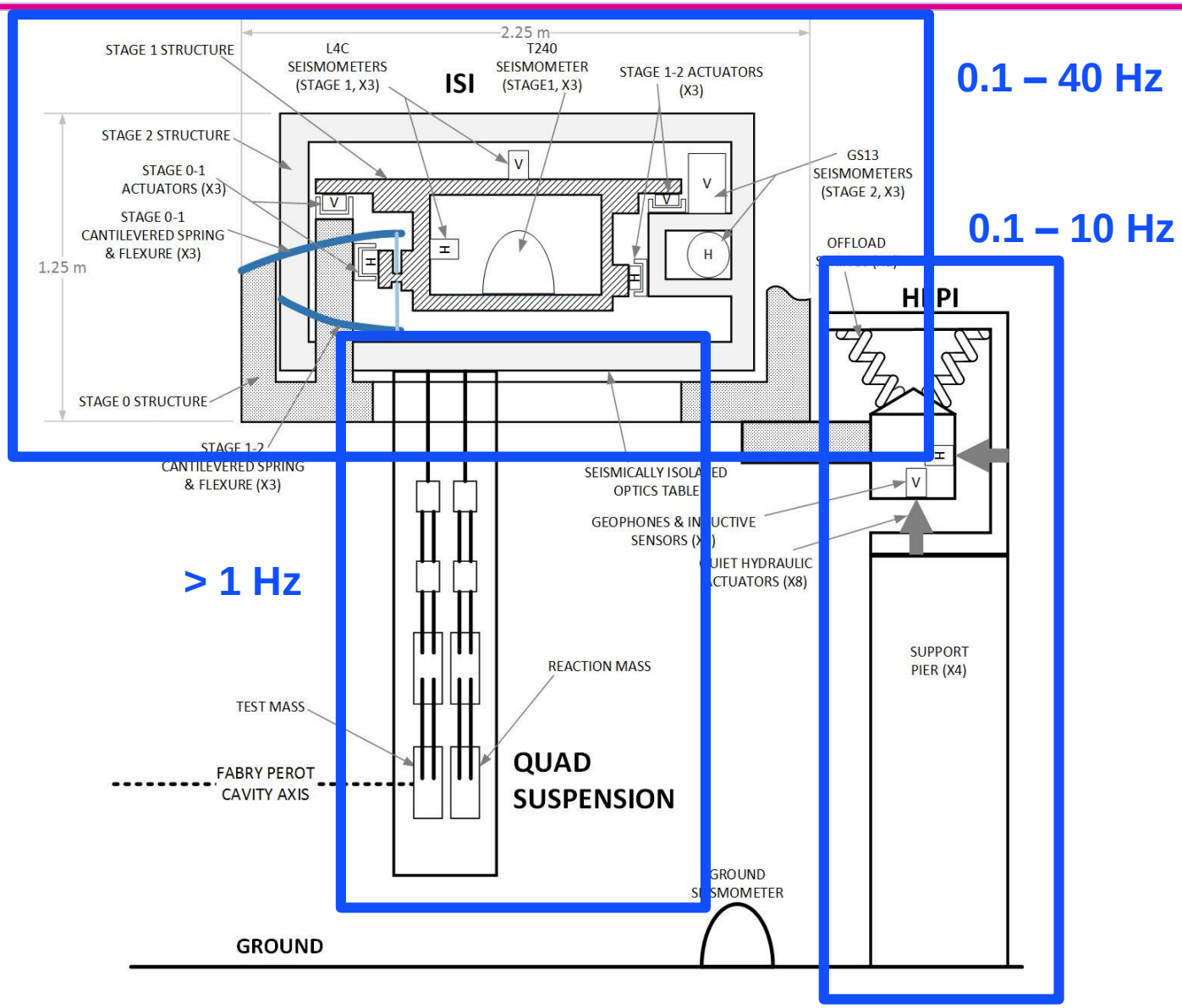


P. Kwee,et al., Opt. Exp. 20, 10617-10634 (2012).



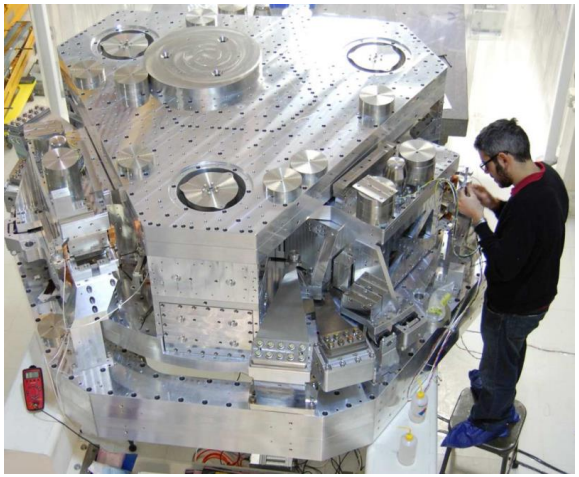
Advanced LIGO Seismic Isolation

3 Stage Approach



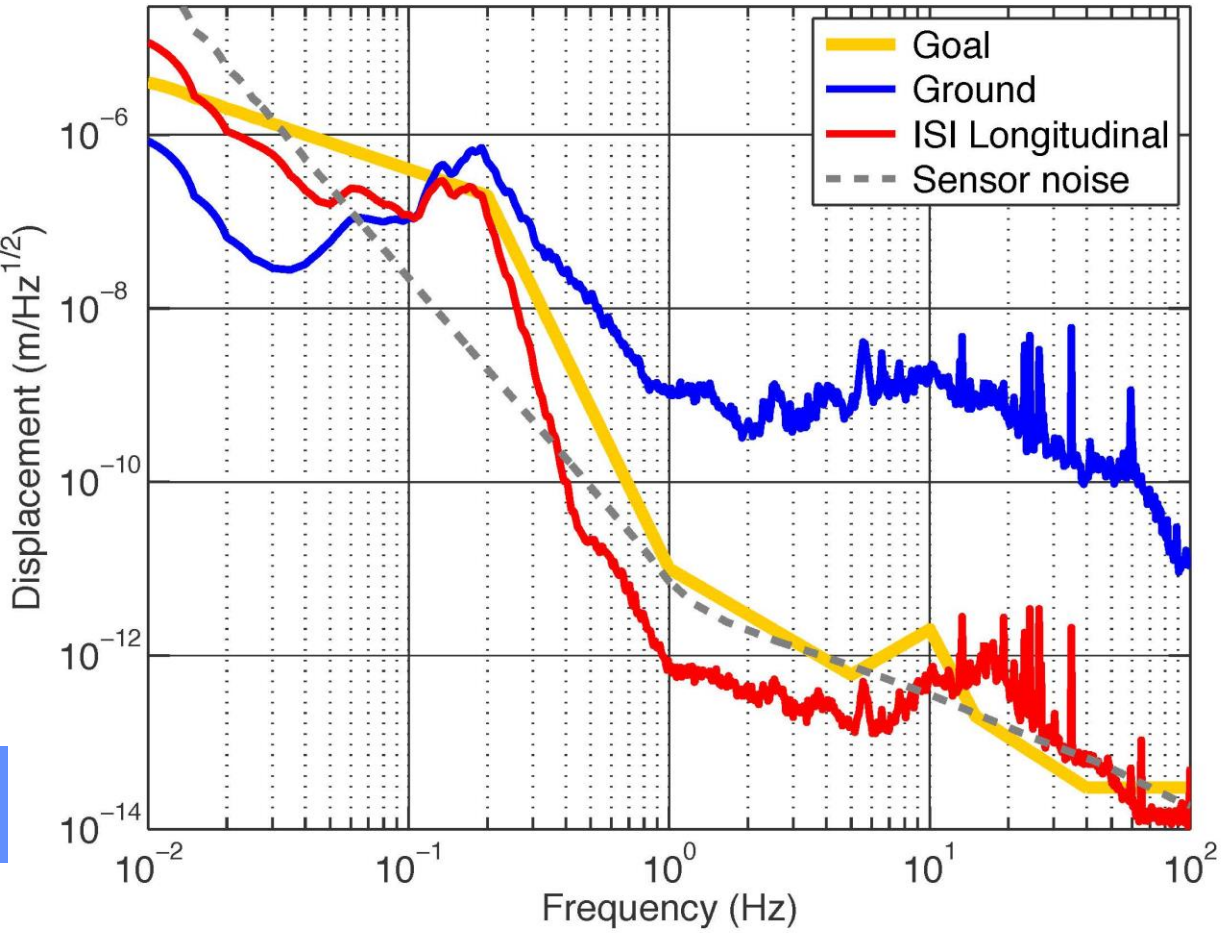
Active Seismic Isolation

Prototype Advanced LIGO Internal Seismic Isolator



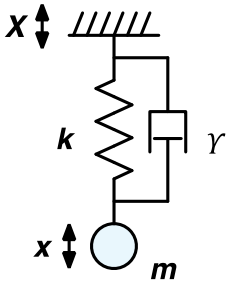
B. P. Abbott, et al. (LIGO Scientific Collaboration) "Advanced LIGO", Classical and Quantum Gravity, 32(7),.074001 (2015).

Measured in-loop ground motion suppression



Advanced LIGO Suspensions

Concept: Harmonic Oscillator

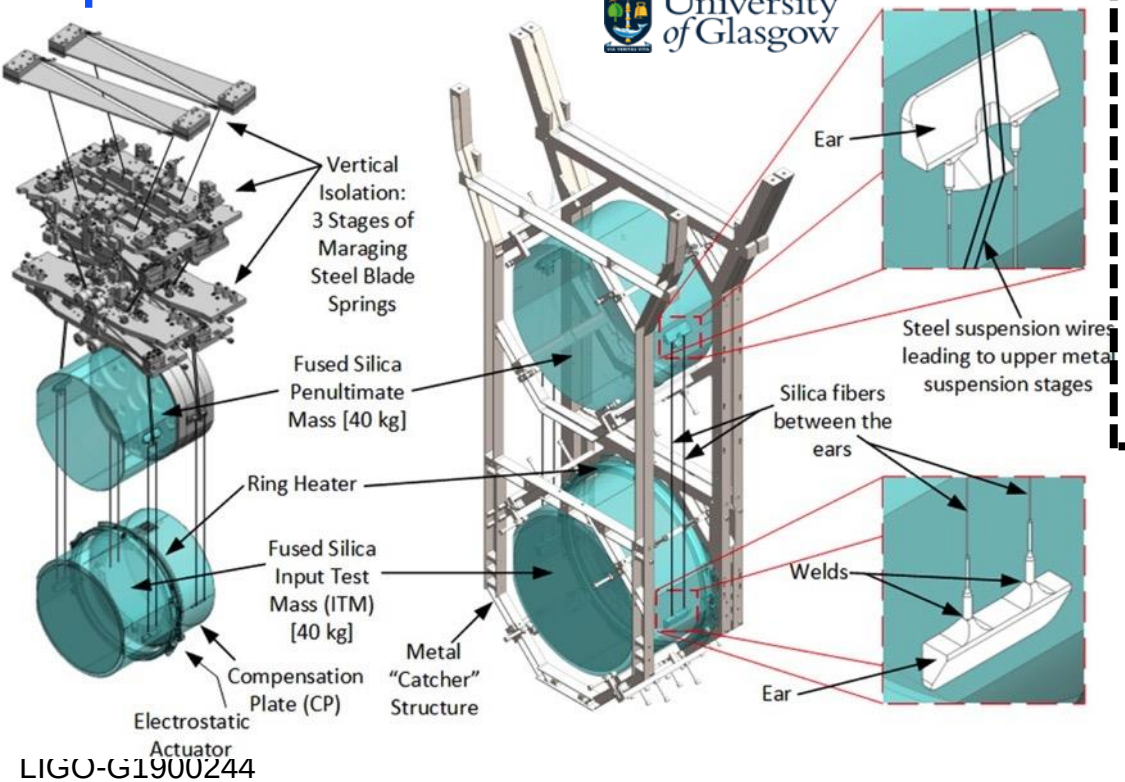


$$m\ddot{x} = -k(x - X) - \gamma(\dot{x} - \dot{X})$$
$$\left(\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2\right)\tilde{x} = \left(\omega_0^2 + i\frac{\gamma}{m}\omega\right)\tilde{X}$$
$$\frac{\tilde{x}}{\tilde{X}} = \frac{\omega_0^2 + i\frac{\gamma}{m}\omega}{\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2}$$

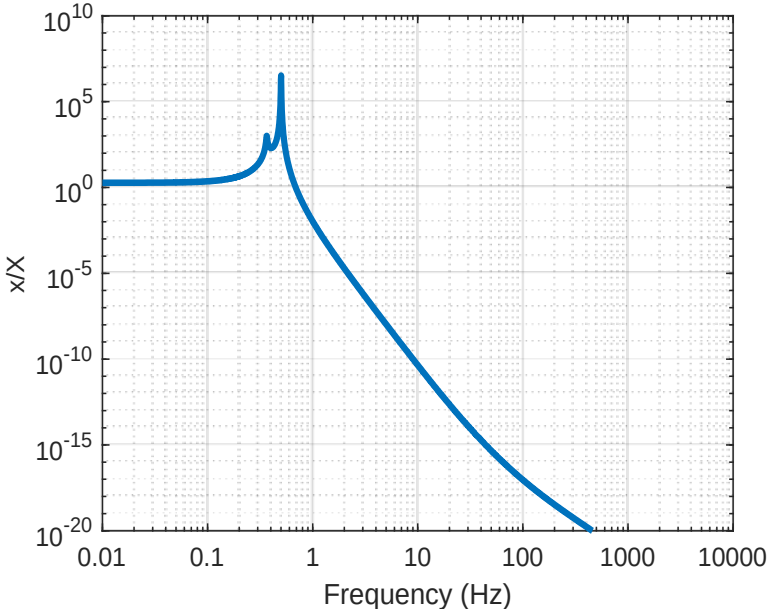
Implementation:

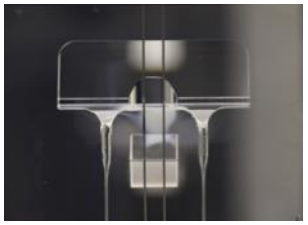
Collaboration w/ U. Glasgow

University of Glasgow



4 Stage Transfer Function:

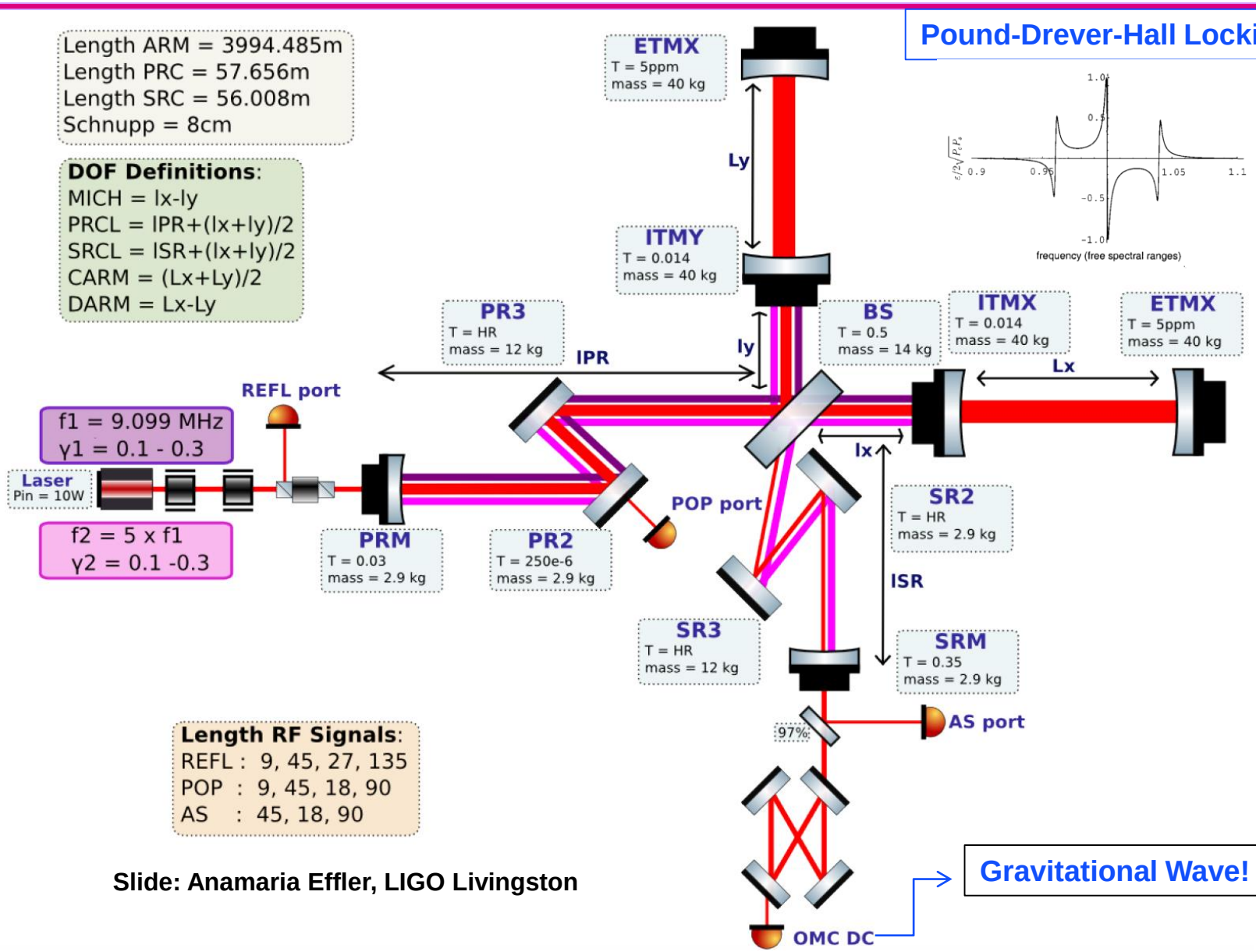




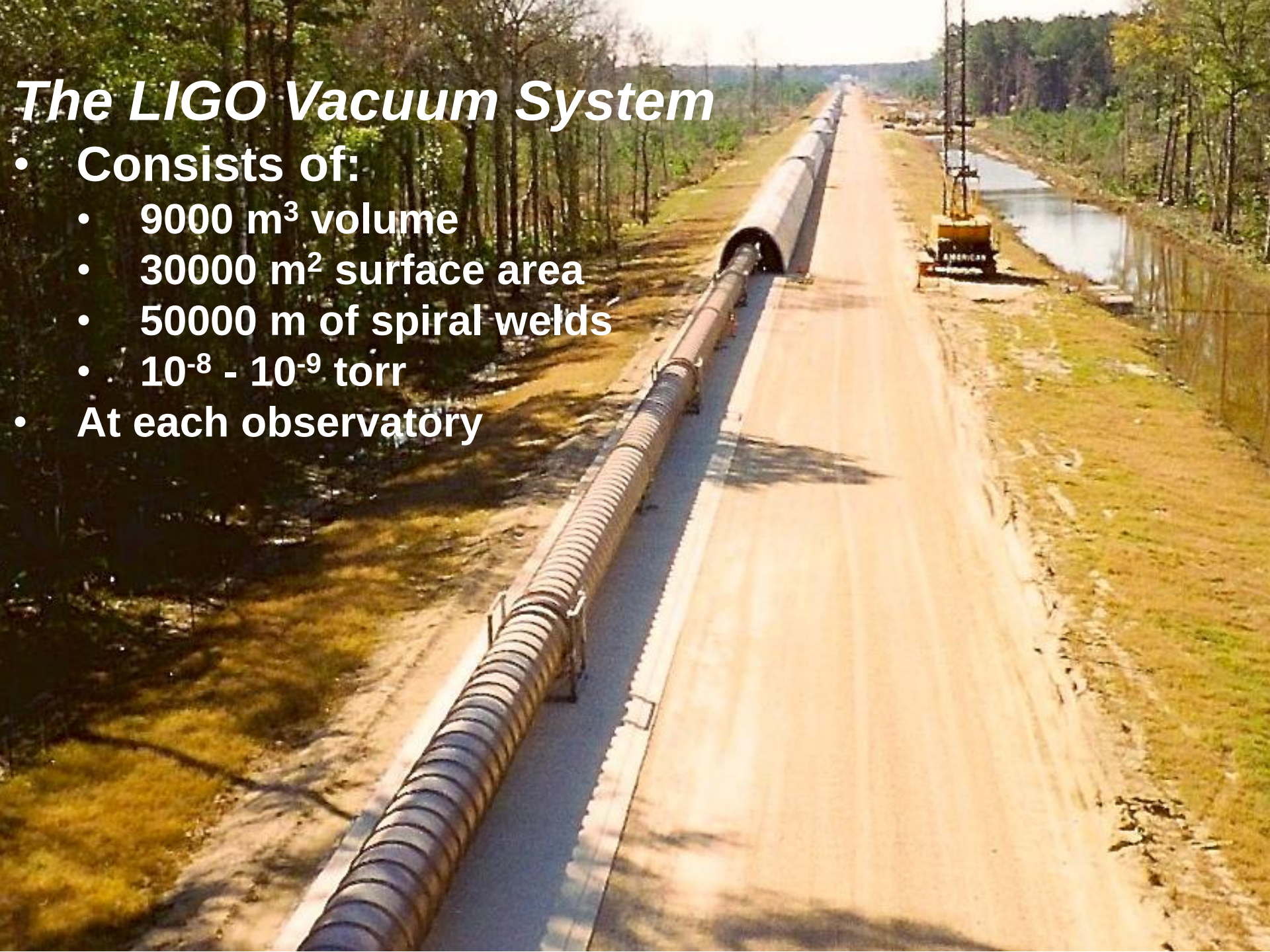
Upper 'ear'

Lower 'ear'

Advanced LIGO = Servo Control



Slide: Anamaria Effler, LIGO Livingston



The LIGO Vacuum System

- Consists of:
  - 9000 m^3 volume
  - 30000 m^2 surface area
  - 50000 m of spiral welds
  - 10^{-8} - 10^{-9} torr
- At each observatory

Precision Interferometry = Understanding Measurement Noises

Fundamental Noises:

I. Displacement Noises

→ **ΔL(f)**

- Seismic noise
- Radiation Pressure
- Thermal noise
  - Suspensions
  - Optics

II. Sensing Noises

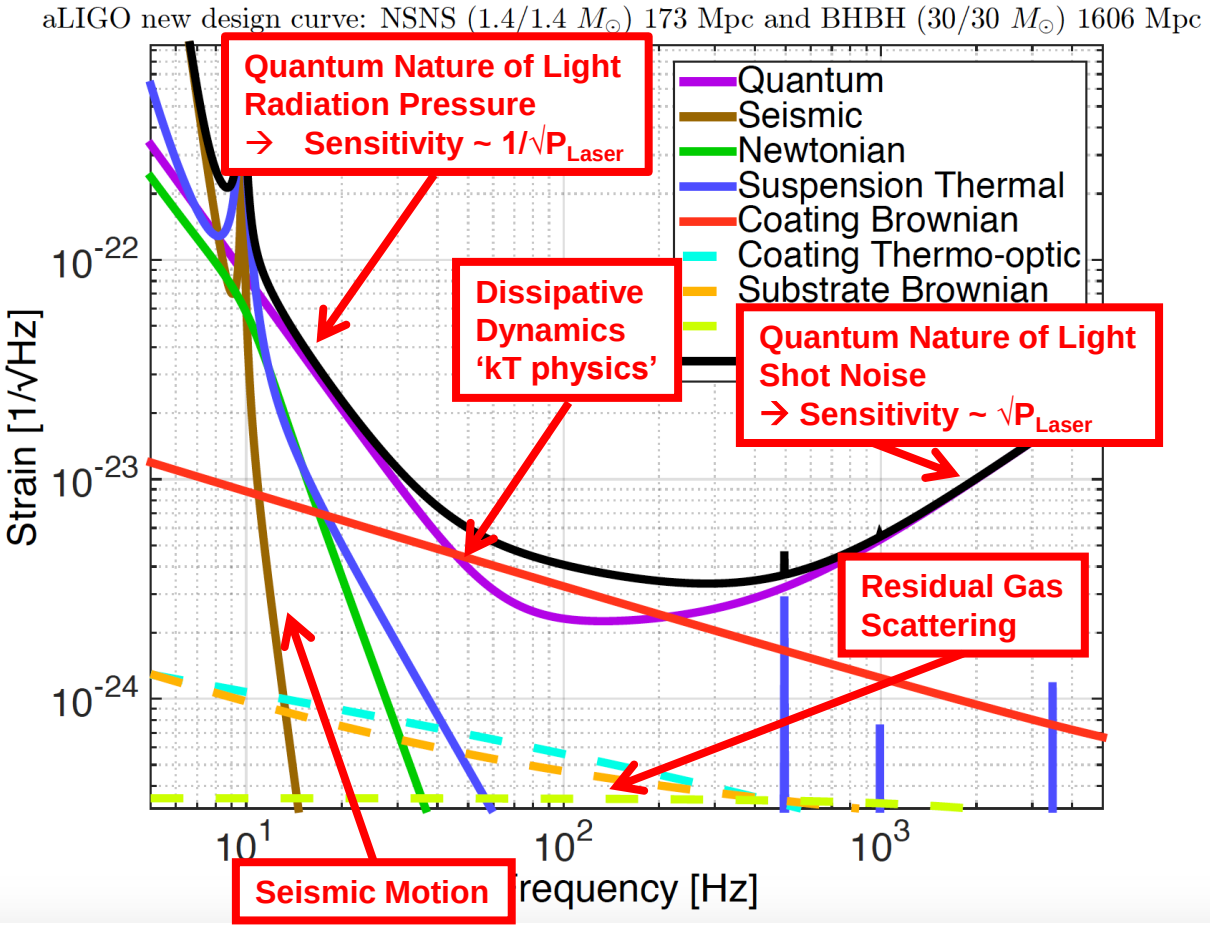
→ **$\otimes t_{photon}(f)$**

- Shot Noise
- Residual Gas

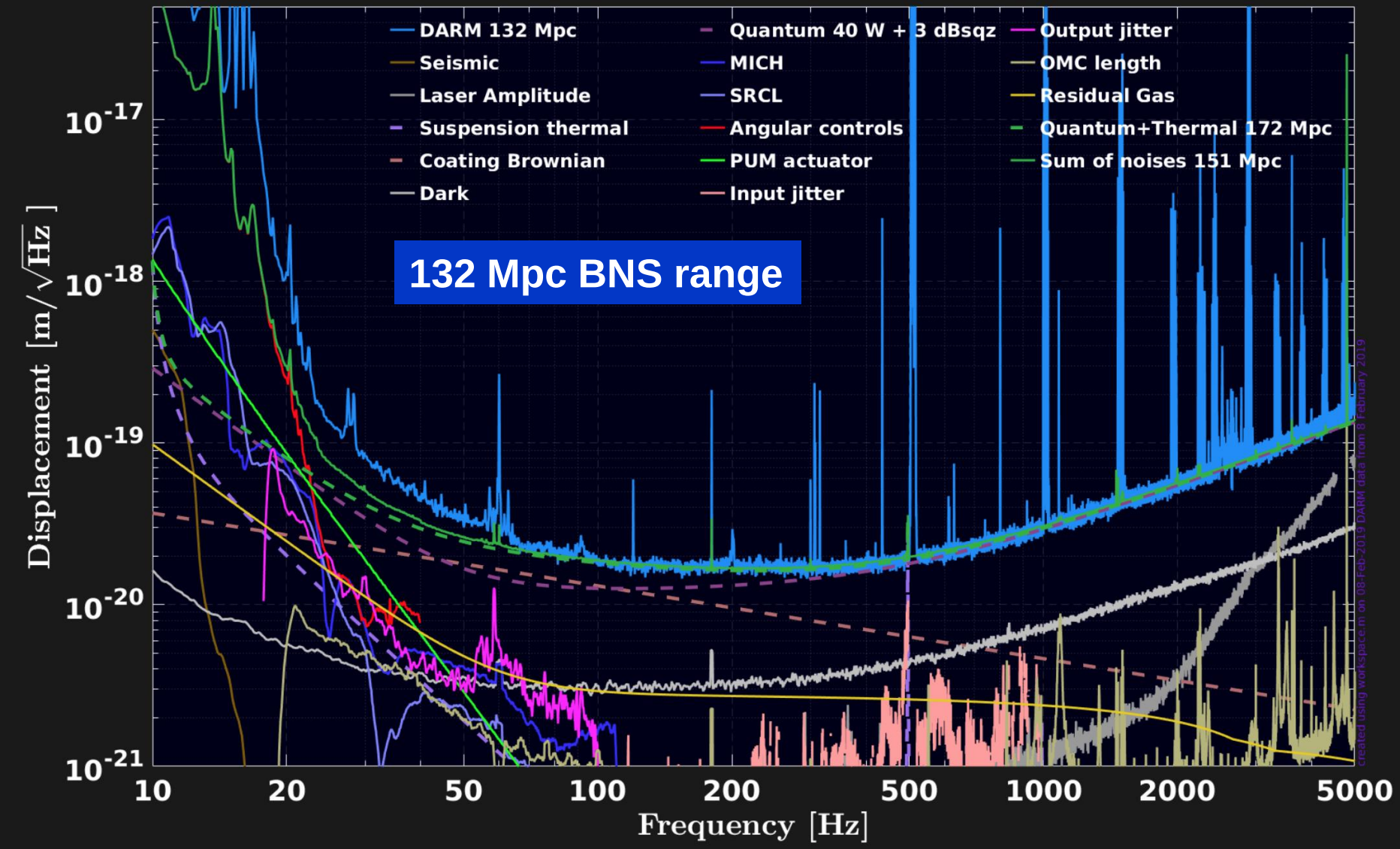
Technical Noises:

→ ***Lots of them…***

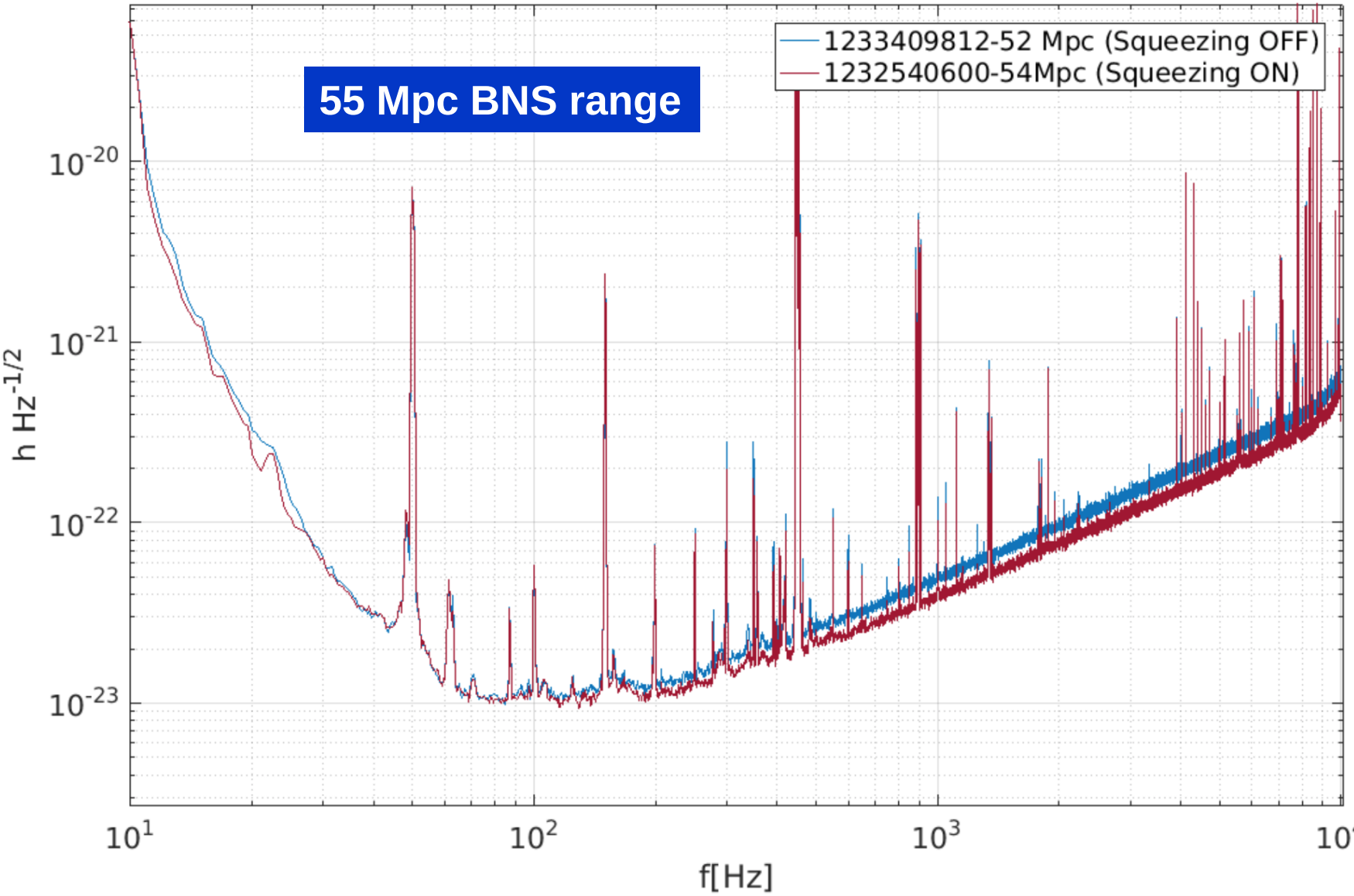
Advanced LIGO Design Noise Budget



Interferometer Sensitivity: LIGO Livingston



Interferometer Sensitivity: Virgo



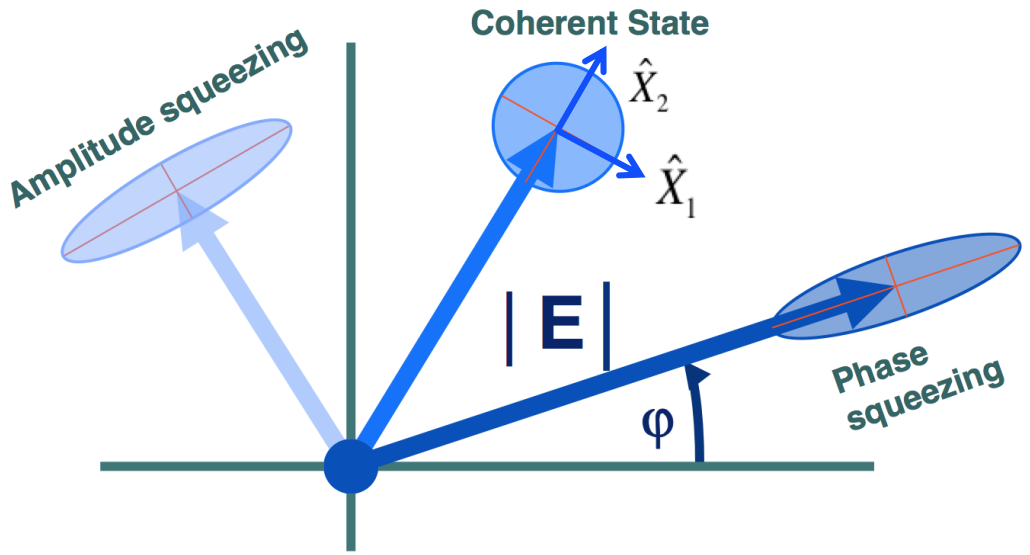
Quantum Engineering Light: Squeezed States

- **Electromagnetic fields are quantized:**

$$\hat{E} = \hat{X}_1 \cos \omega t + i \hat{X}_2 \sin \omega t$$

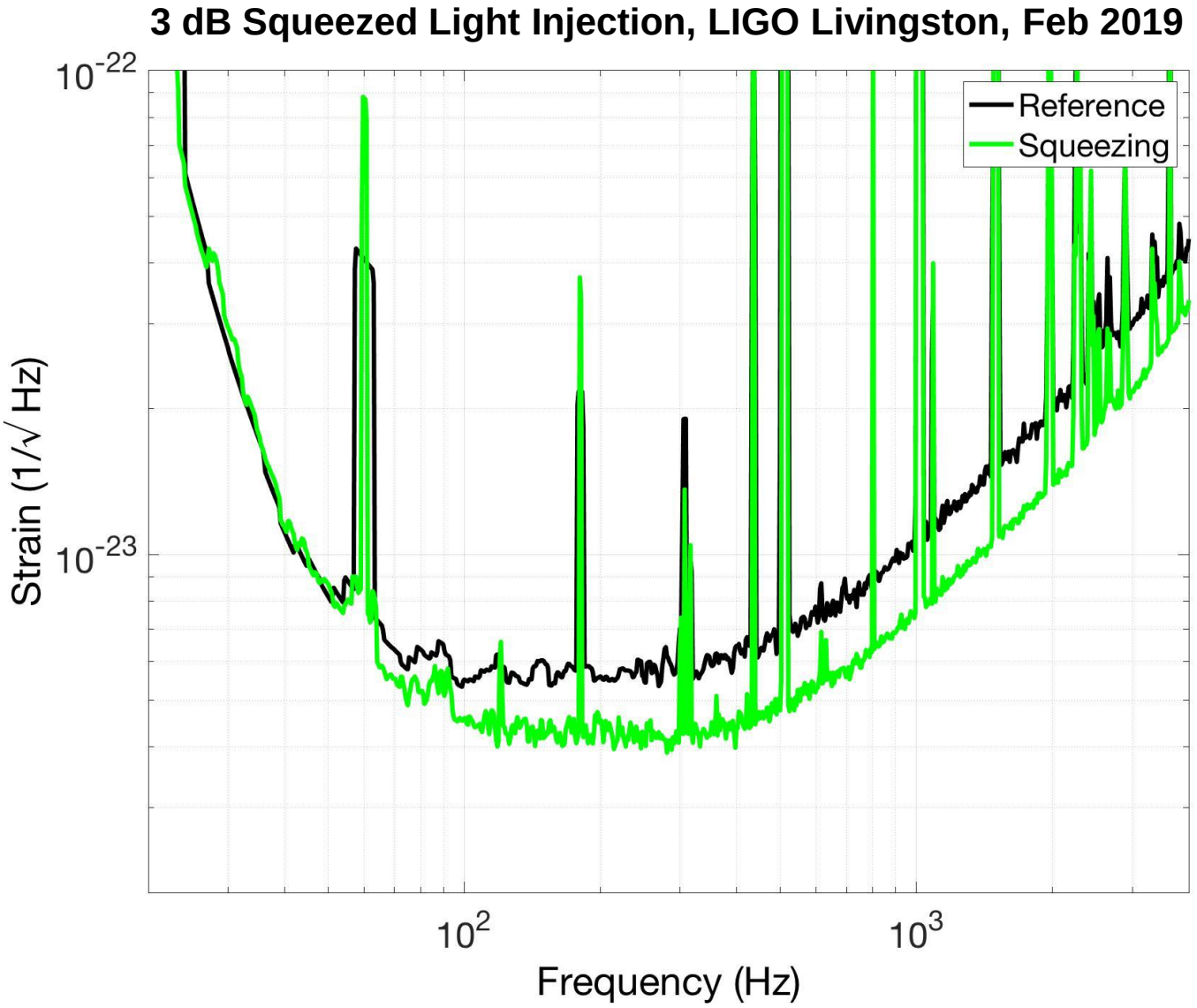
- **Quantum fluctuations exist in the vacuum state:**

$$\langle (\Delta \hat{X}_1)^2 \rangle \langle (\Delta \hat{X}_2)^2 \rangle \geq 1$$



H. P. Yuen, Phys. Rev. A**13**, 2226 (1976)
C. M. Caves, Phys. Rev. D**26**, 1817 (1982)
Wu, Kimble, Hall, Wu, PRL (1986)

Reducing Sensing Noise with Squeezed Light



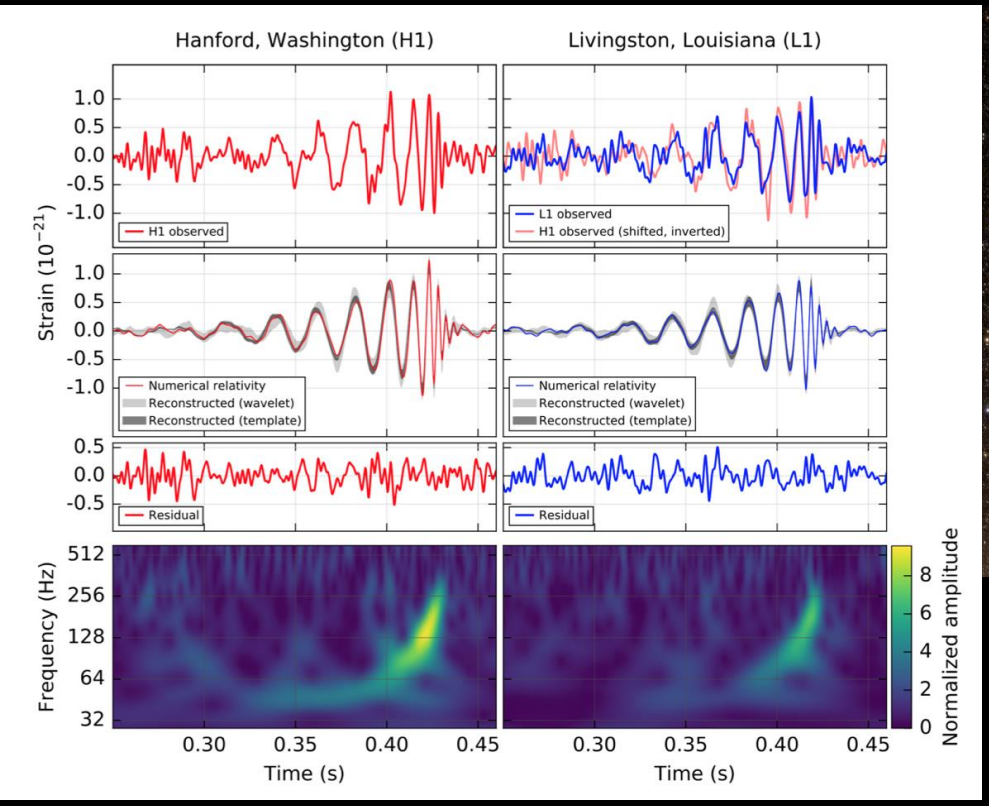
LIGO-G1900244

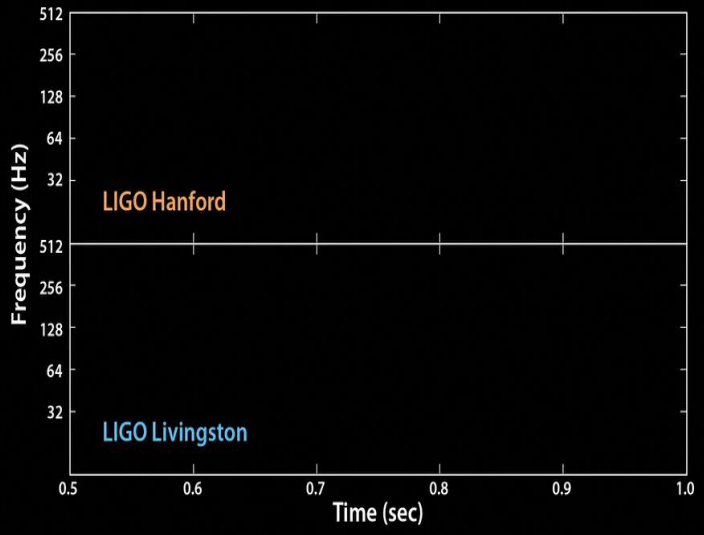
Recent Results:

Binary Black Hole Mergers

Binary Neutron Star Merger GW170817

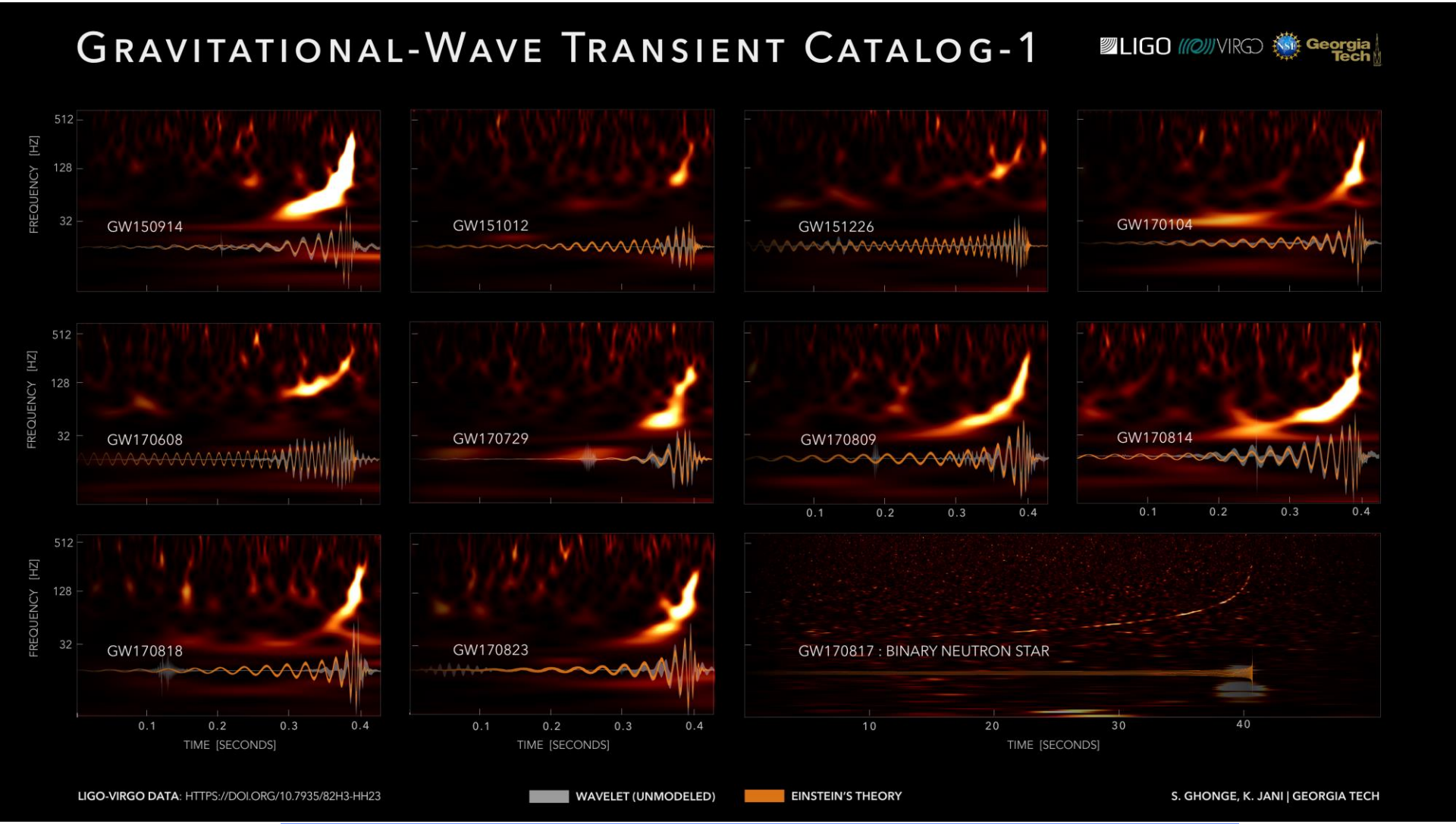
GW150914: The First Binary Black Hole Merger





Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" Phys. Rev. Lett. 116, 061102 (2016)

Just released: GWTC-1 GW Catalog

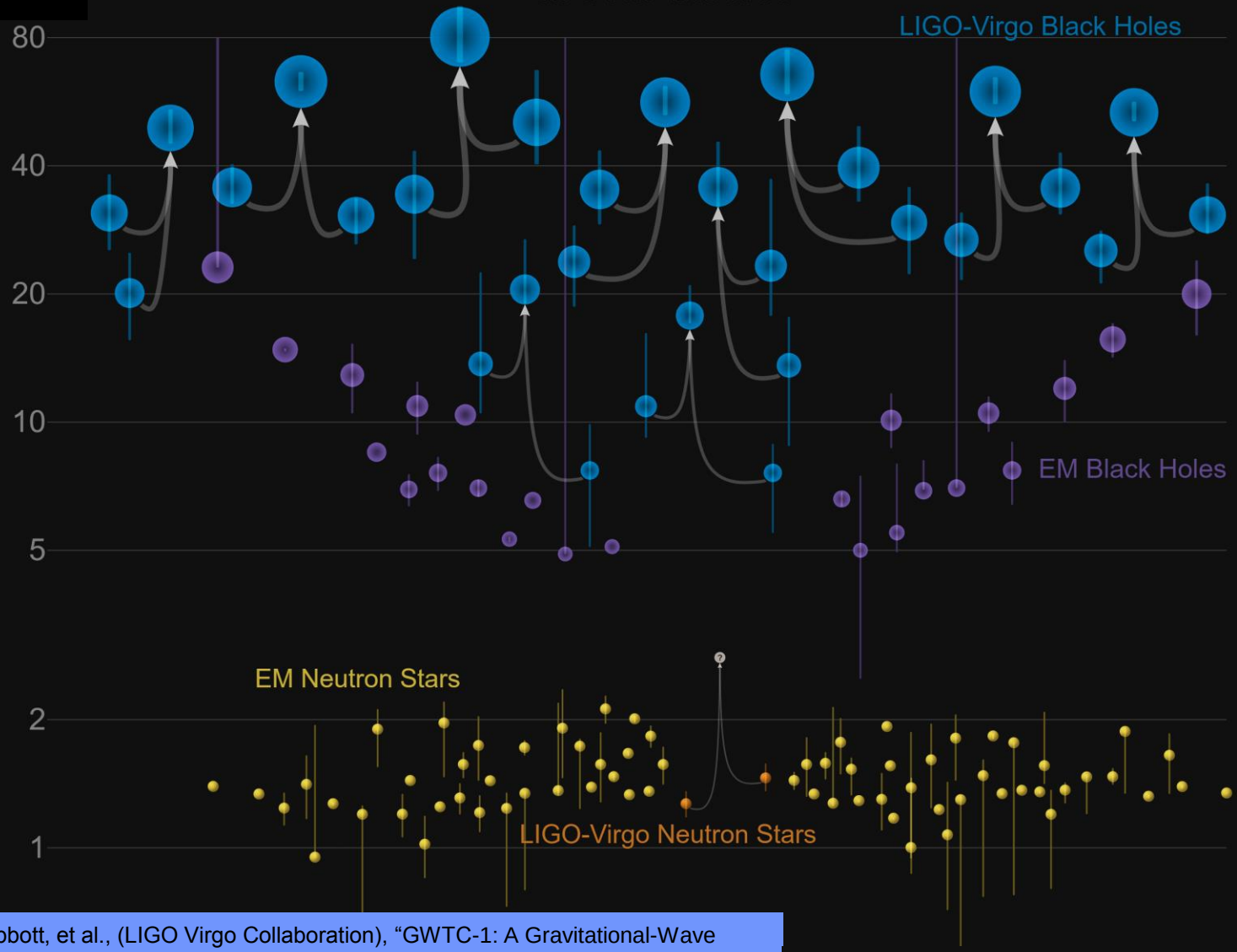


B. P. Abbott, et al., (LIGO Virgo Collaboration), "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" , https://arxiv.org/abs/1811.12907

LIGO

Masses in the Stellar Graveyard

in Solar Masses

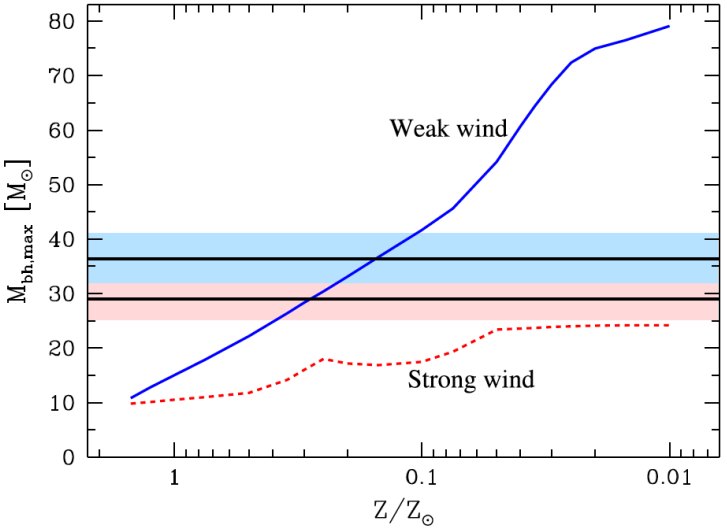


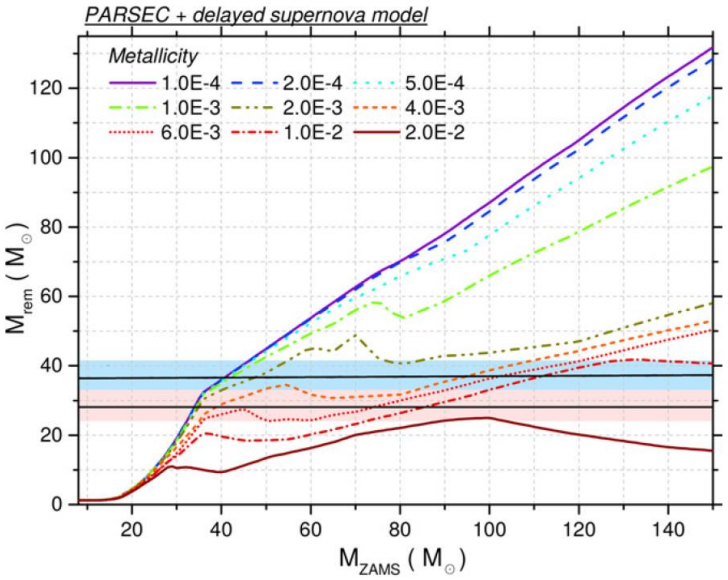
B. P. Abbott, et al., (LIGO Virgo Collaboration), “GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs” , https://arxiv.org/abs/1811.12907

LIGO-Virgo | Frank Elavsky | Northwestern

A Revolution in Black Hole Physics

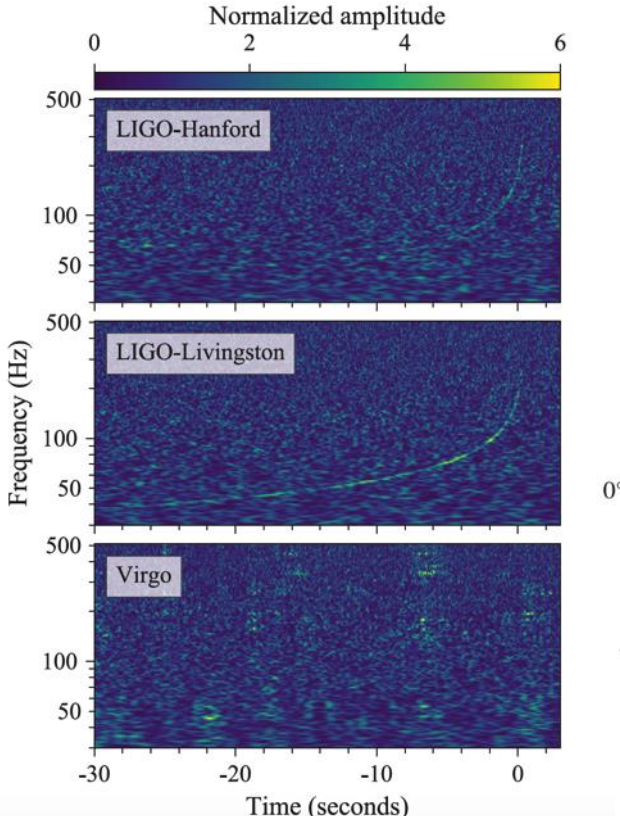
- ***First*** direct detection of gravitational waves
- ***First*** observational confirmation that black holes can form in a binary system and merge in less than a Hubble time
- ***First*** observational confirmation that 'heavy' stellar mass black holes exist
- ***Strong Evidence*** that LIGO's black holes form in low metallicity environments
- **Many open questions!**
  - (Binary) Black hole mass spectrum?
  - Spins? → Formation channels?
  - Primordial black holes? Dark matter component?



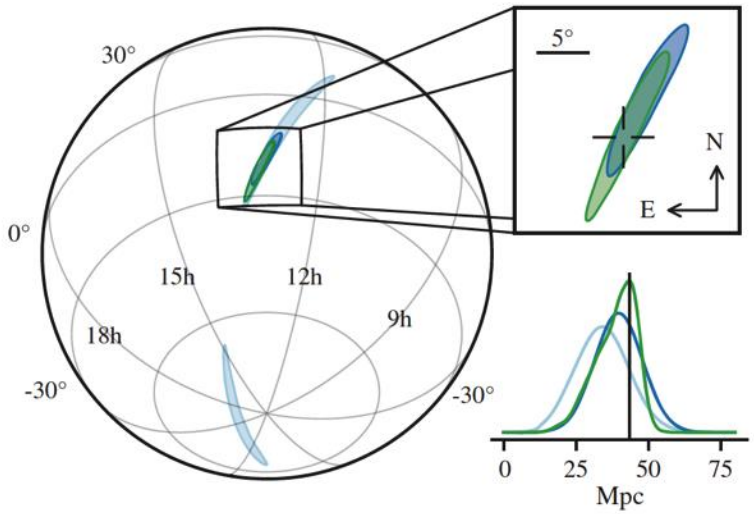


Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Astrophysical Implications of the Binary Black Hole Merger GW150914" Astrophys. J. Lett 818:L22 (2016)

GW170817: The First Detected Binary Neutron Star Merger

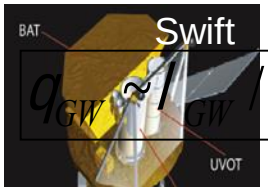


Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)

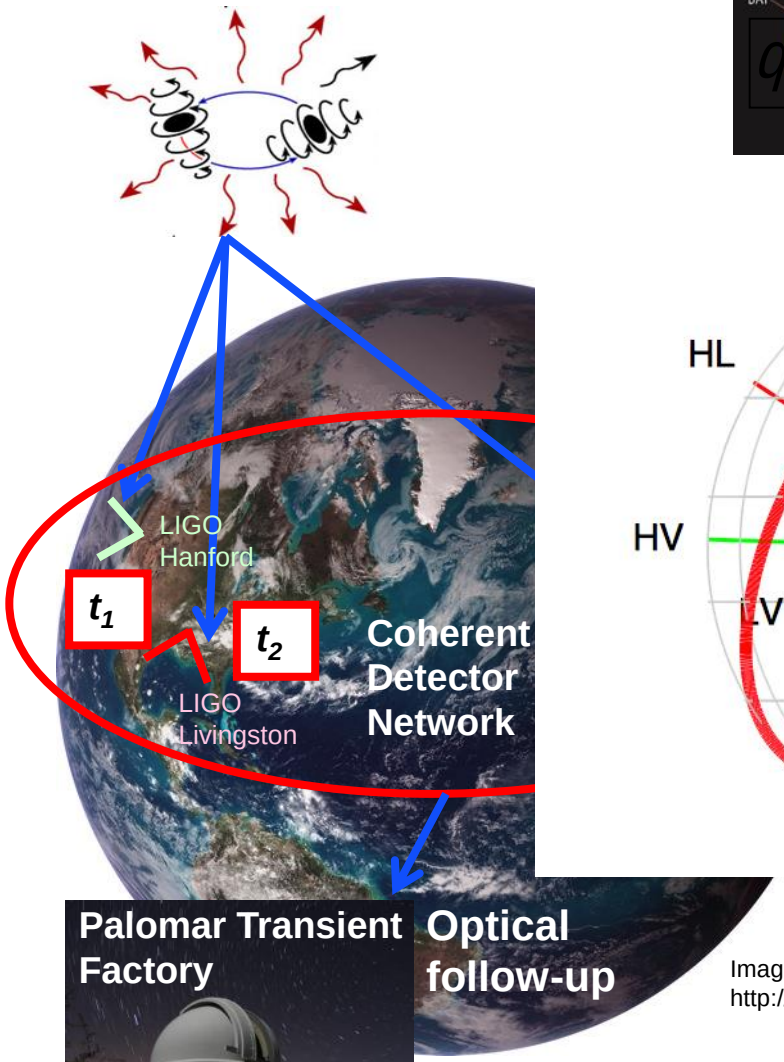


	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Enabling multi-messenger astronomy with gravitational waves



$$q_{GW} \simeq l_{GW} / d \sim \text{few degrees}$$



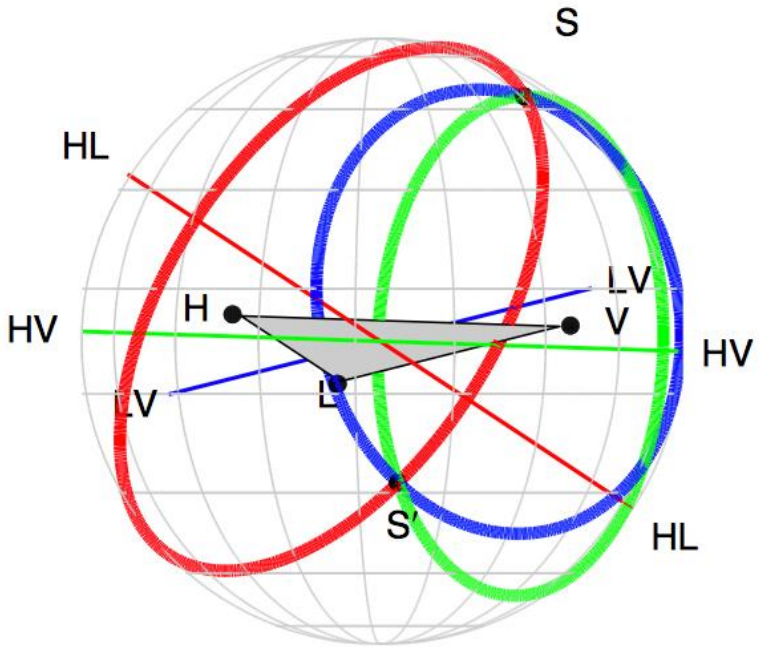
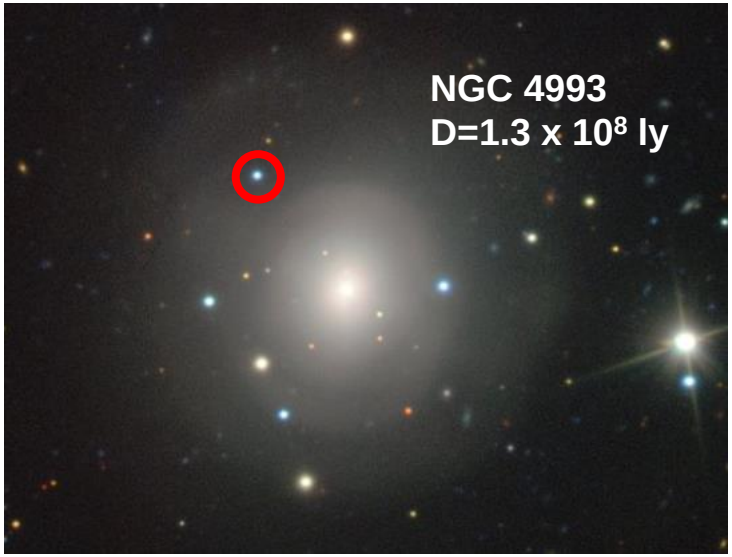


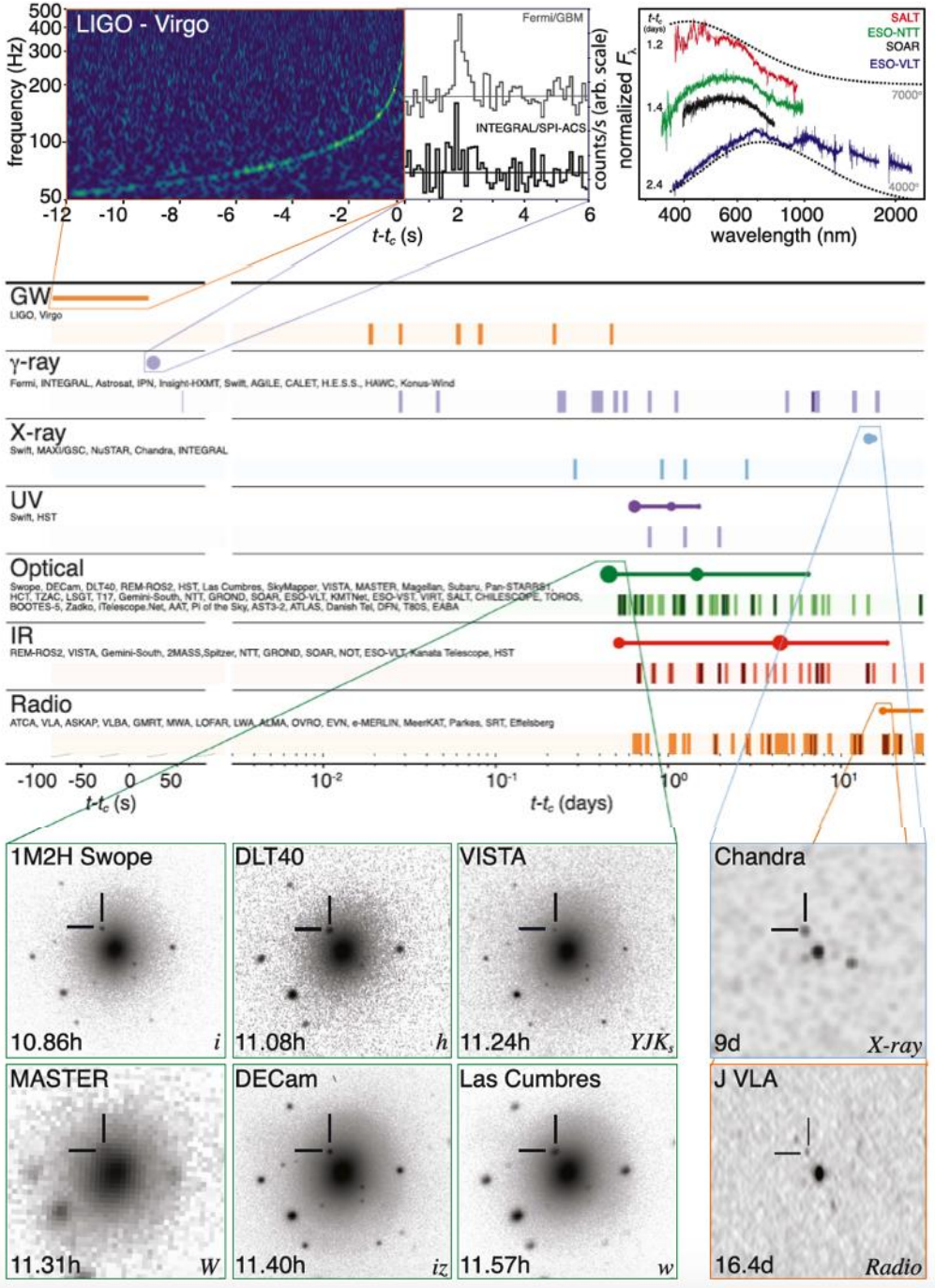
Image
http://e

Abadie, et al, (LSC & Virgo Collaborations) Astron. Astrophys. **541** (2012) A155.
Nissanke, Kalsiwal, Georgieva, Astrophysical J. **767** (2013) 124.
Singer, Price, et al., Astrophysical J., 795 (2014) 105.

A Multi-messenger Astronomical Revolution!



Credit: European Southern Observatory
Very Large Telescope



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” Astrophys. J. Lett., 848:L12, (2017)

Testing General Relativity
Are Gravitons Massless?

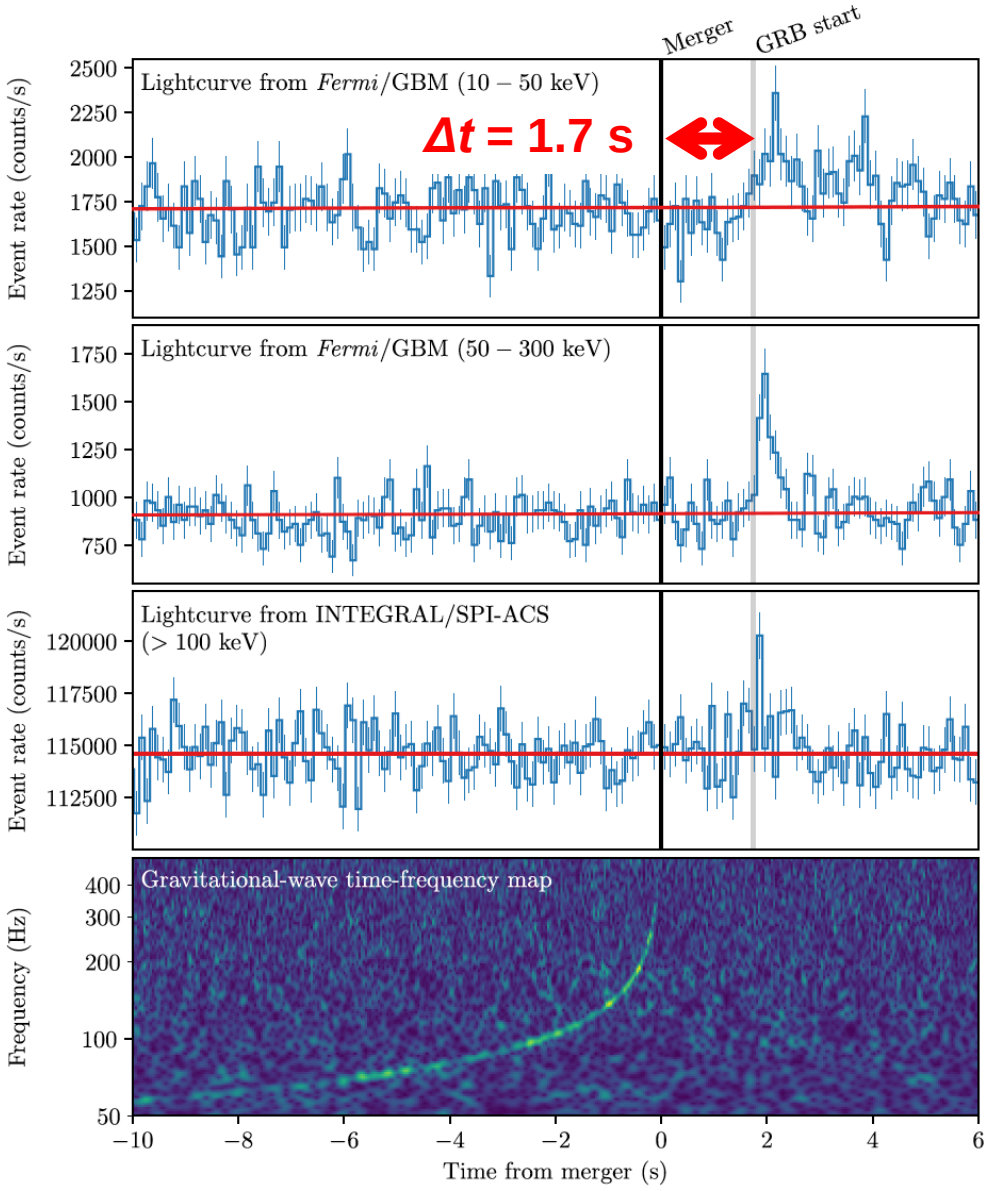
- GW170817 provides a stringent test of the speed of gravitational waves

$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- Δt =1.74 +/- 0.05 s
- $D \approx 26$ Mpc
  - » Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$-3 \times 10^{-16} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}$$

- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle

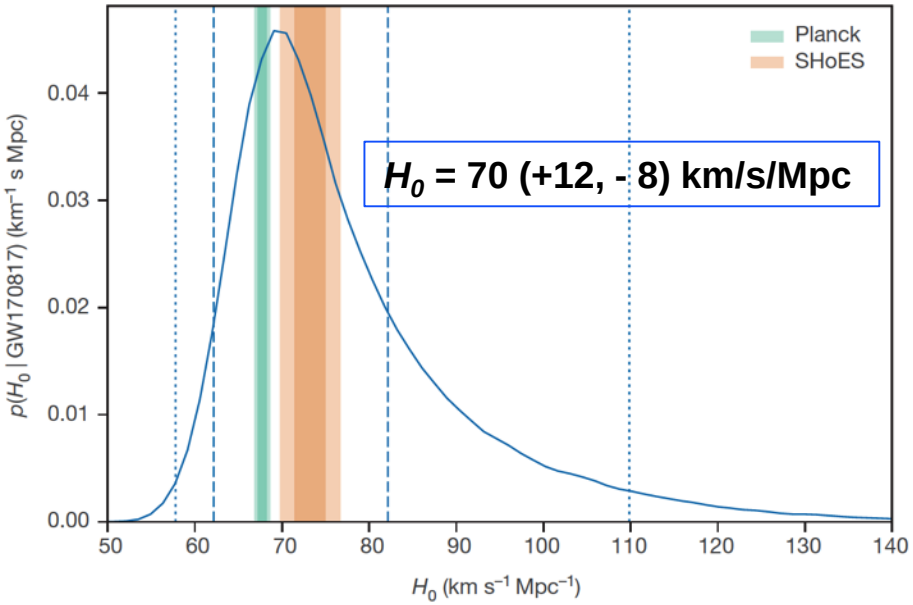


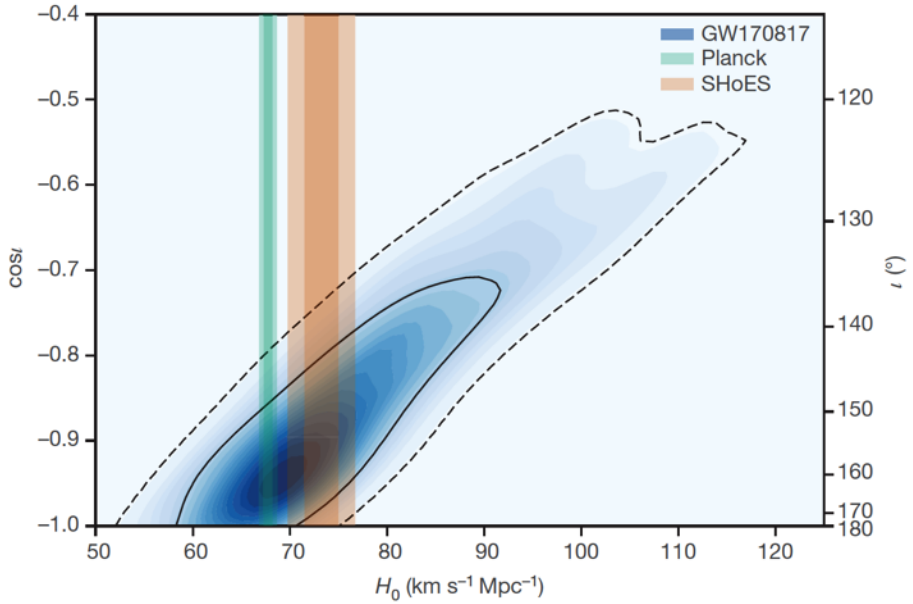
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

Cosmology: Measuring the Hubble Constant

- Gravitational waves are ‘standard sirens’, providing absolute measure of luminosity distance d_L
- GW detections can be used to determine H_0 directly if red shift is known:

$$c\,z = H_0\,d_L$$

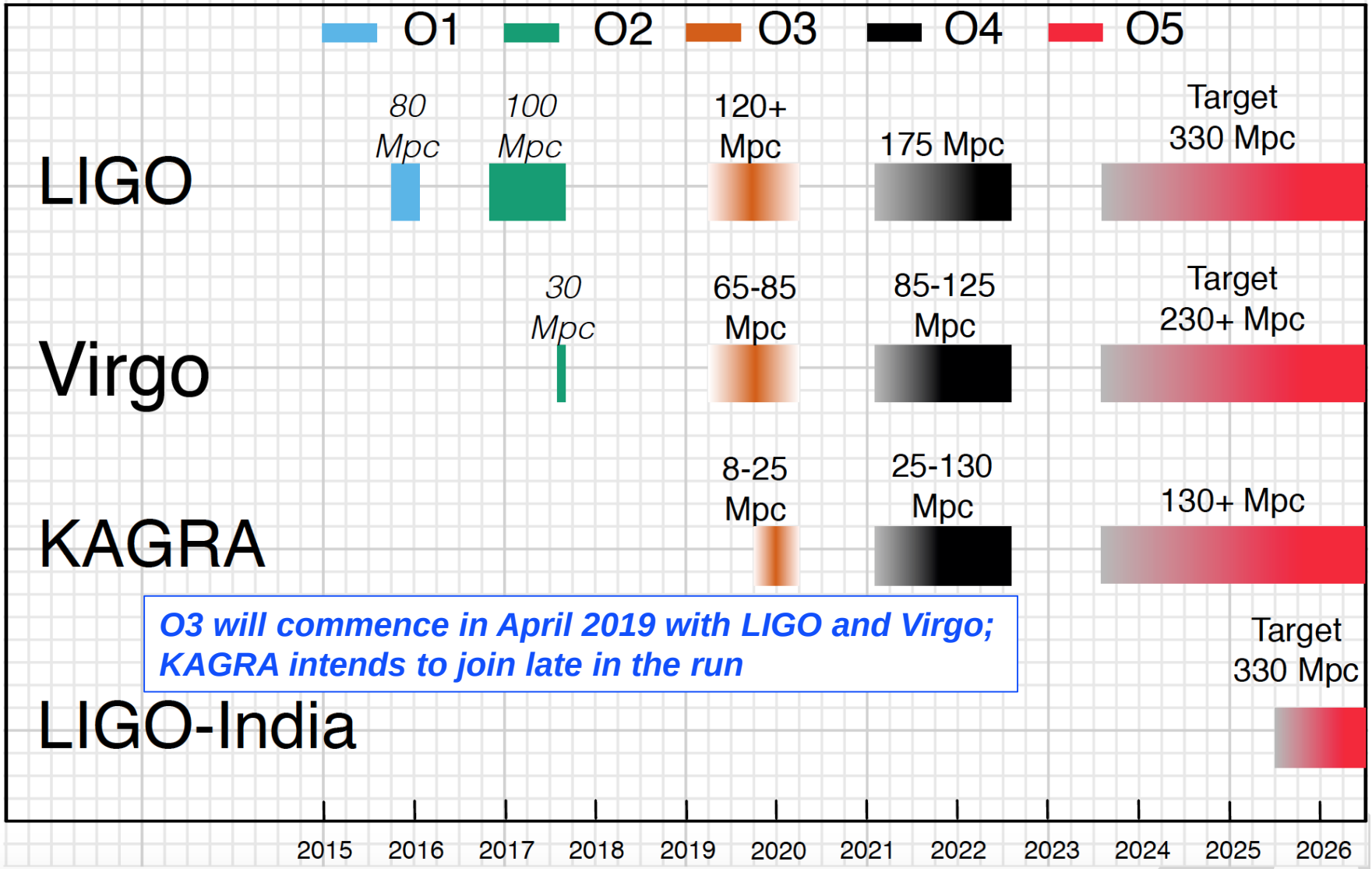




Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* **551**, 85–88 (2017).

The Future of Ground-based Gravitational-wave Detectors

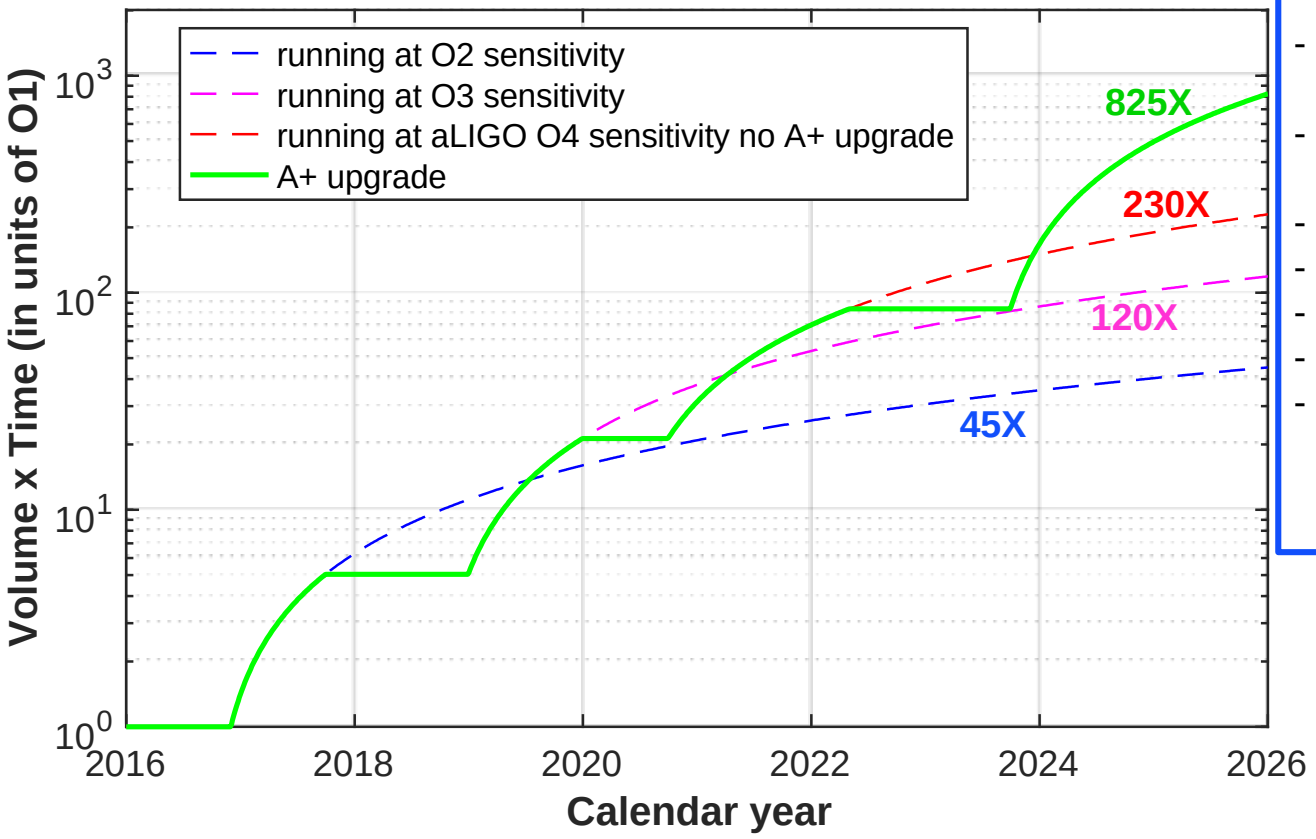
Planned GW Observing Runs



GW Science is Sensitivity Driven

1) Rates: $$N_{events} = T_{observing} \int \int R(z)\, dz\, d\Omega$$

Binary Neutron Stars



2) *Many sources require higher SNR to uncover new astrophysics!!*

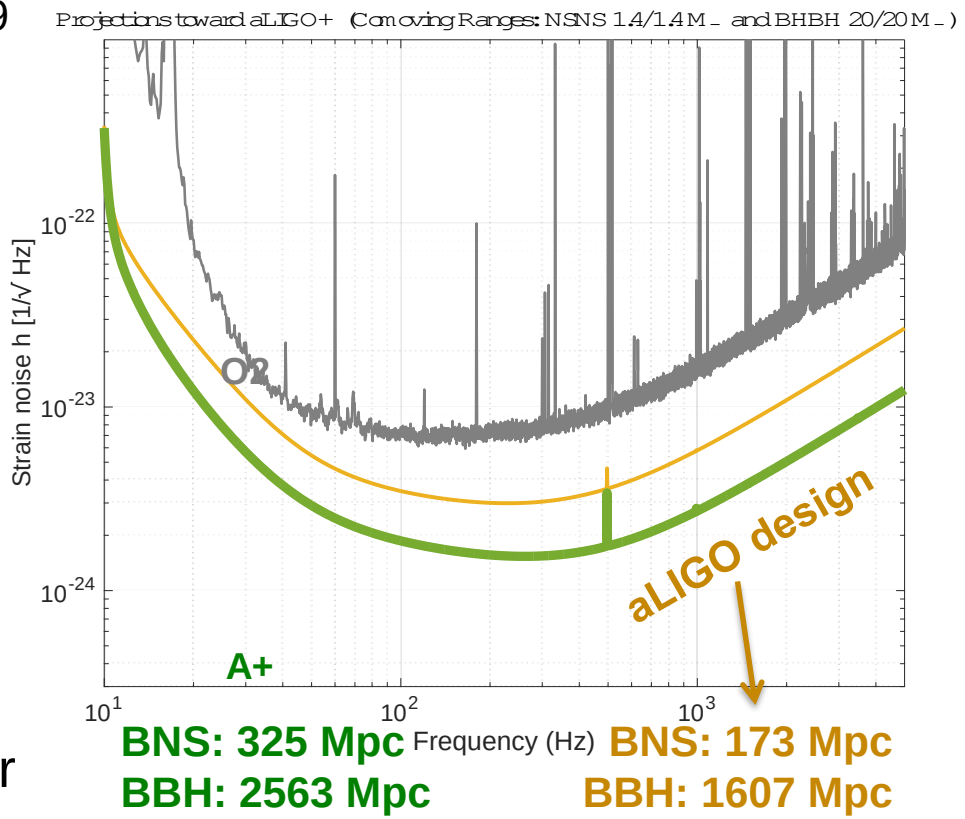
- **tidal disruption in BNS mergers**
- **tests of alternative theories of gravity**
- **Black hole ringdowns**
- **Stochastic background**
- **Isolated neutron stars**
- **Galactic supernova**
- **Surprises!**

LIGO-G1900244

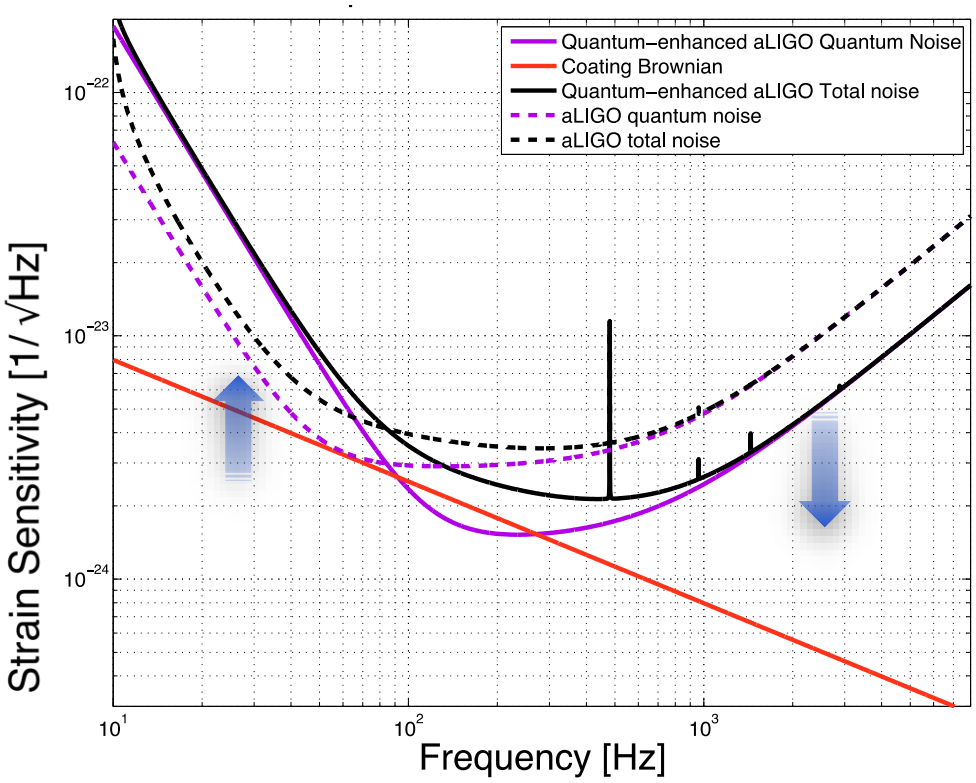
2024: Advanced LIGO 'A+'

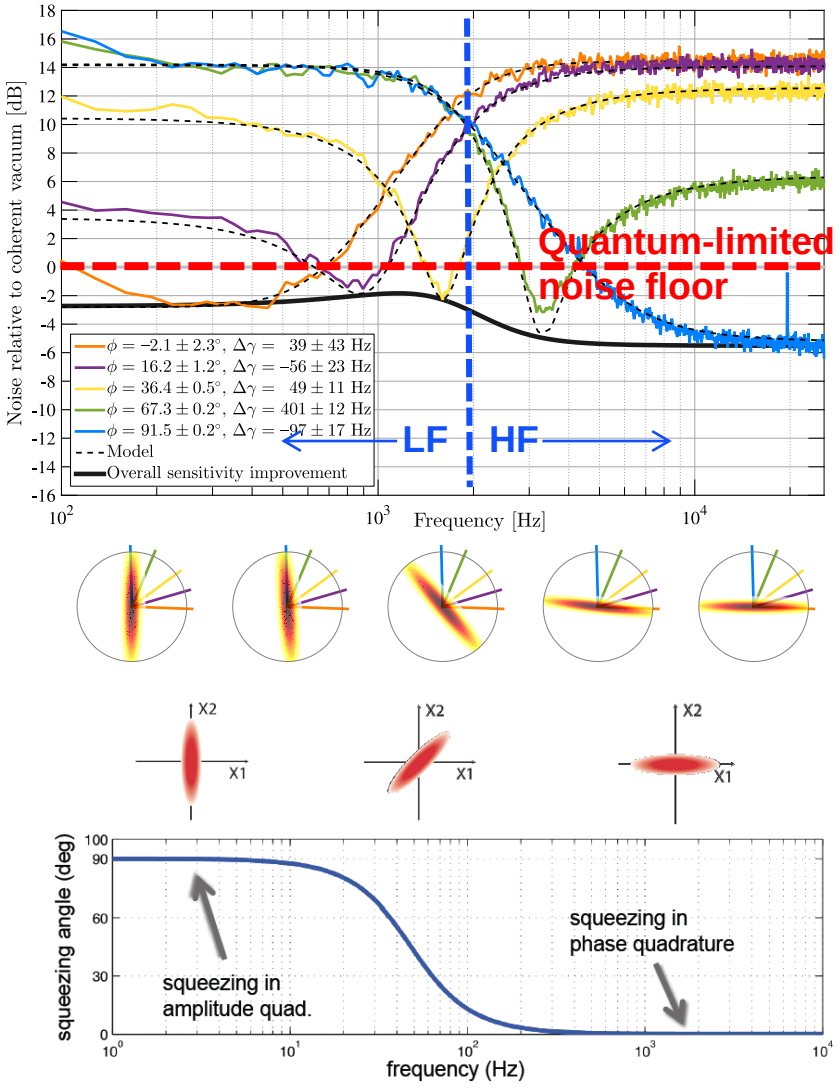
- 'Mid-scale' upgrade of the Advanced LIGO interferometers
- Sensitivity improvement over ALIGO:
  - » 1.4/1.4 $M_\odot$ BNS inspiral range by ~ 1.9 to 325 Mpc
  - » 30/30 $M_\odot$ binary black hole inspiral range by ~1.6 to > 2.5 Gpc
- → ***Greater event rate than Advanced LIGO***
- → ***Higher SNR CBC events***

- Employs *frequency-dependent squeezing* & lower thermal noise mirror coatings
- Currently planning for a 1.5-2 year run duration beginning mid 2024 or early 2025



Quantum Engineering Light II: Frequency Dependent Squeezing

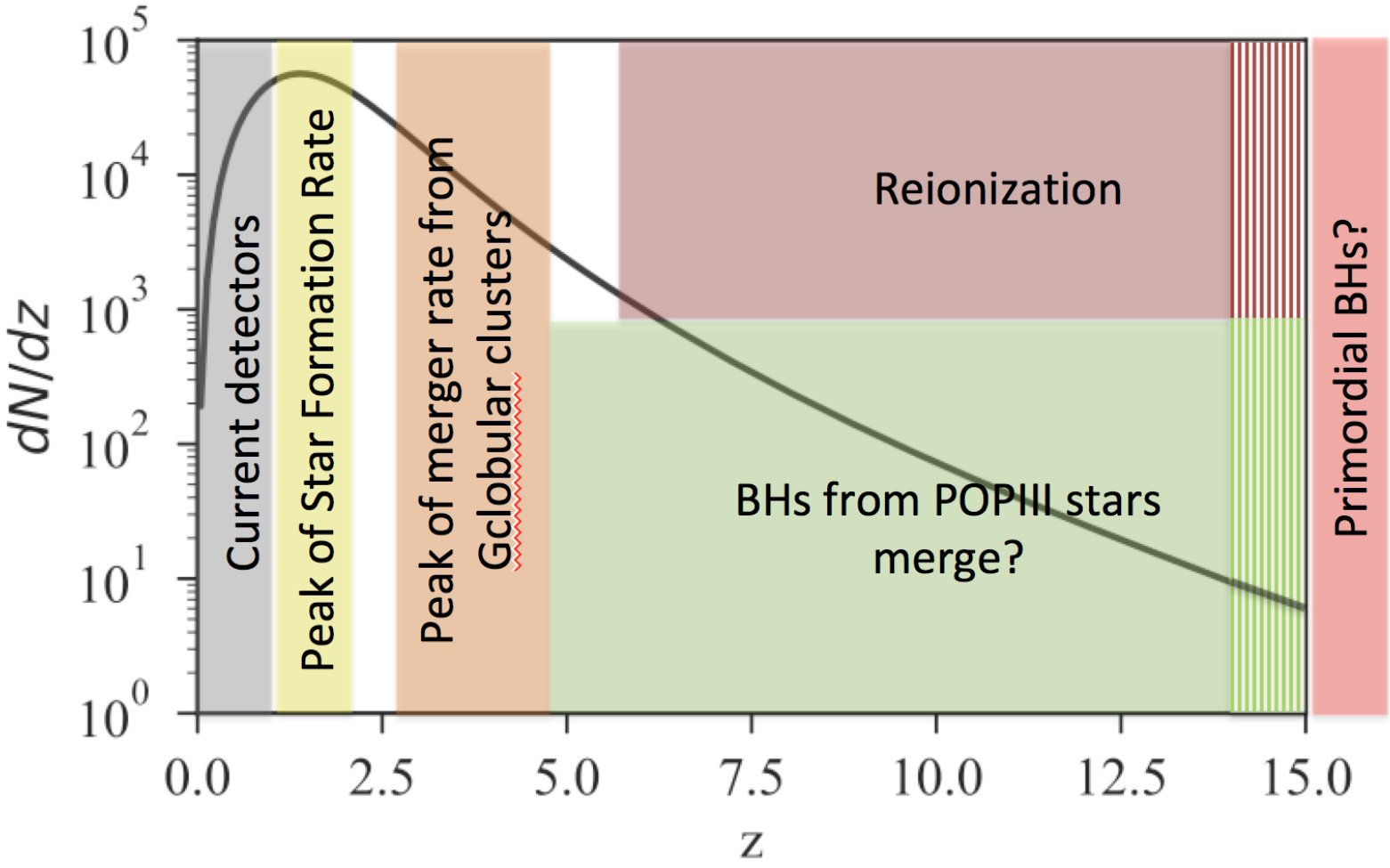




Concept: Kimble, Levin, Matsko, Thorne, Vyatchanin, Phys. Rev. D (2001)

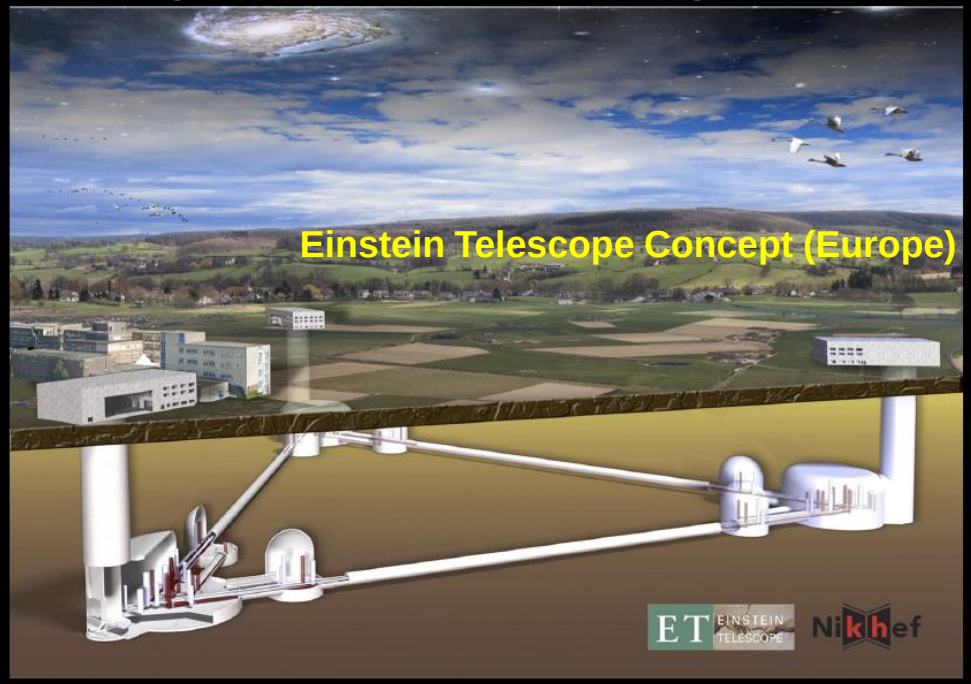
Experiment: Oelker, et al., "Audio-band Frequency-dependent Squeezing", Phys. Rev. Lett. **116**, 041102 (2016).

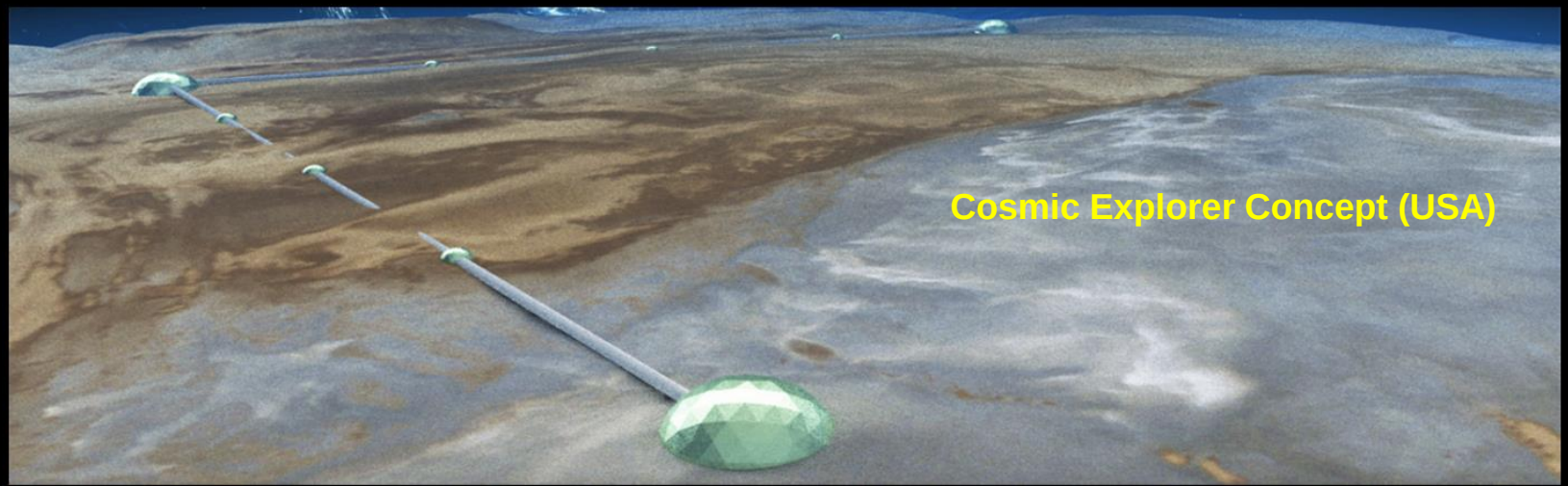
The Longer Term: New Observatories, New Technologies



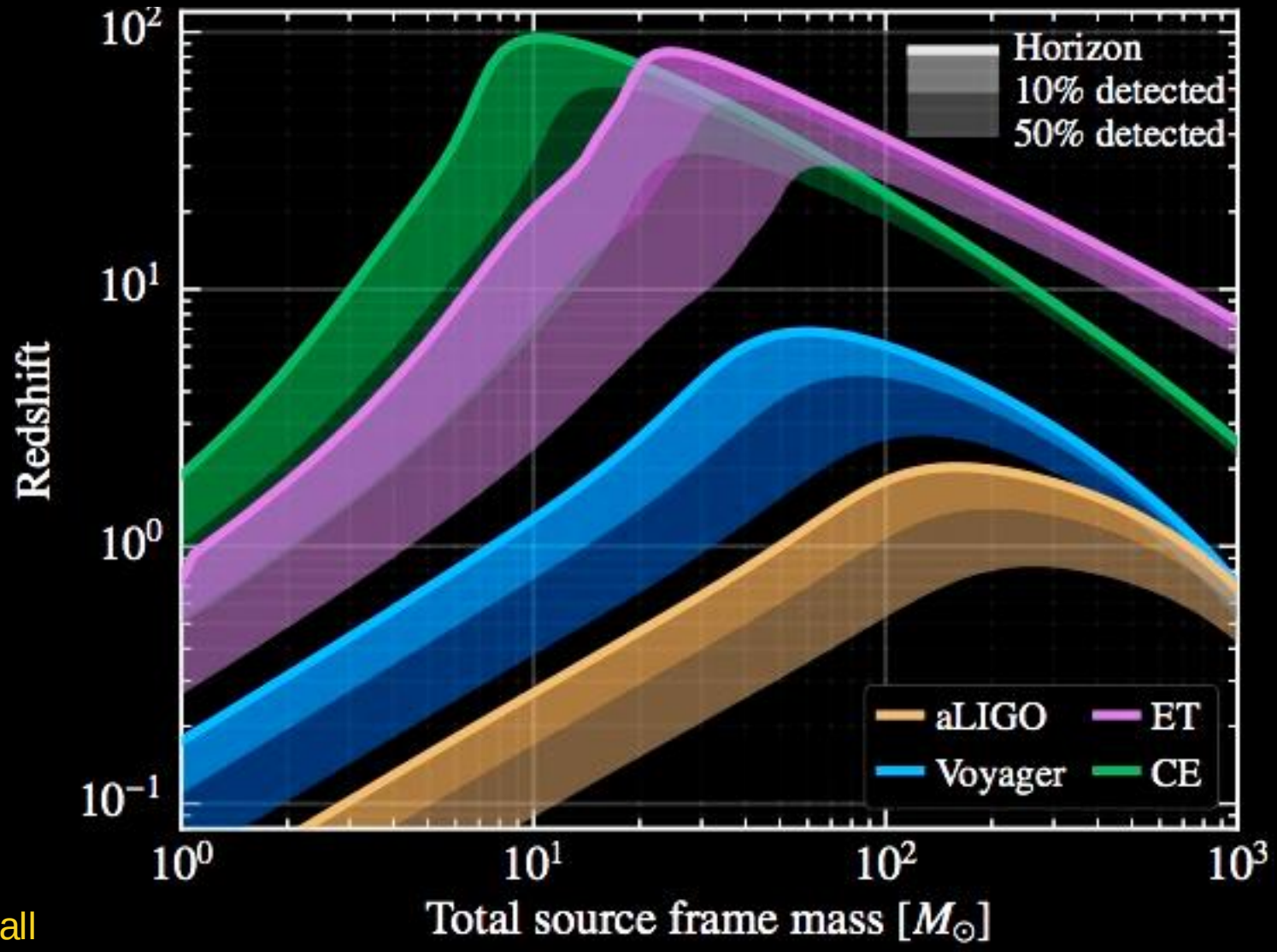
Credit: Salvatore Vitale (MIT)

‘Third Gen’ Ground-based Observatories: Einstein Telescope and Cosmic Explorer in the 2030s





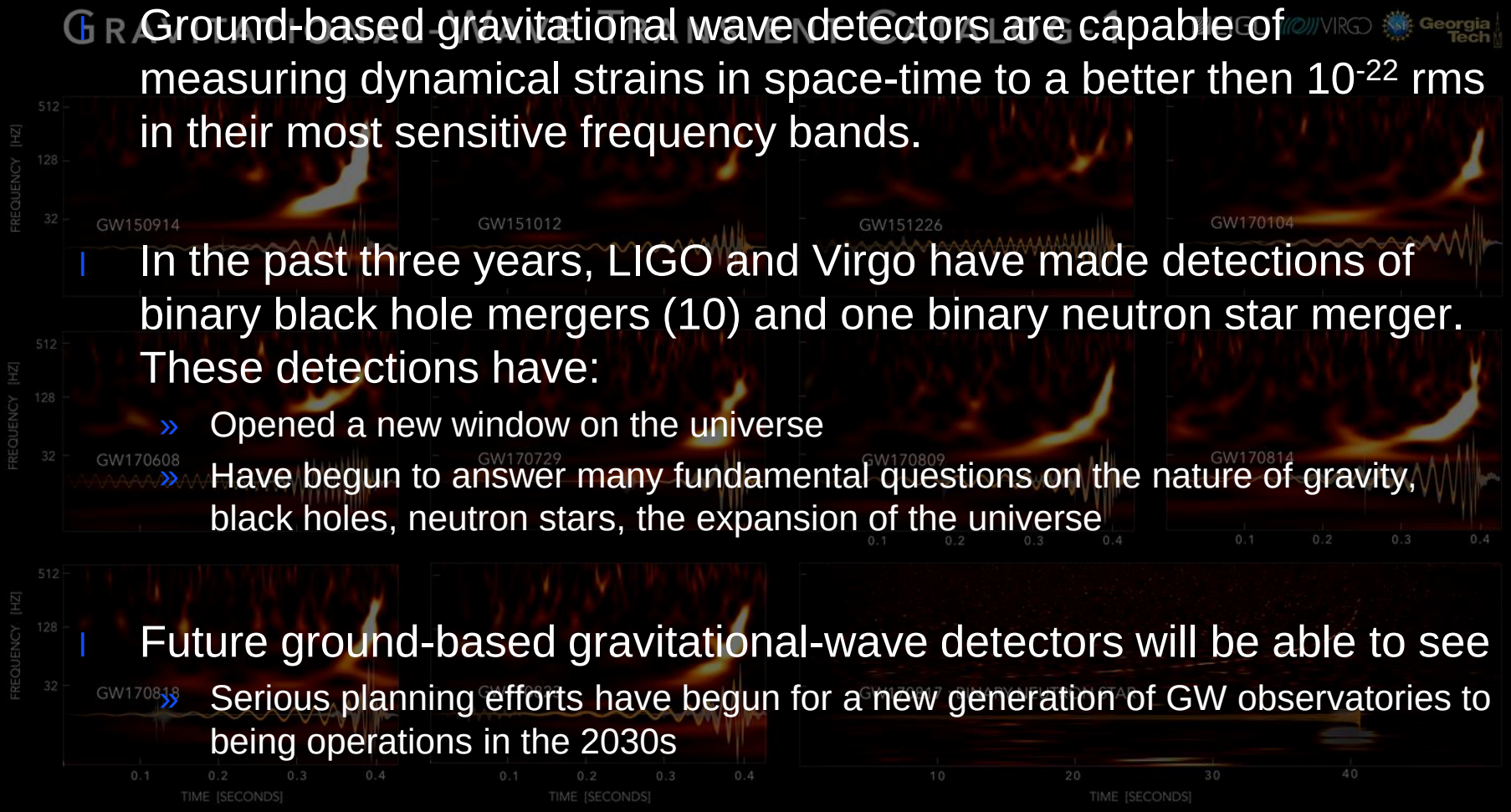
OBSERVING EARLIEST MOMENTS OF FORMATION OF STARS AND STRUCTURE



Evan Hall

Conclusions

- Ground-based gravitational wave detectors are capable of measuring dynamical strains in space-time to a better then 10^{-22} rms in their most sensitive frequency bands.



- In the past three years, LIGO and Virgo have made detections of binary black hole mergers (10) and one binary neutron star merger. These detections have:
  - Opened a new window on the universe
  - Have begun to answer many fundamental questions on the nature of gravity, black holes, neutron stars, the expansion of the universe
- Future ground-based gravitational-wave detectors will be able to see
  - Serious planning efforts have begun for a new generation of GW observatories to being operations in the 2030s

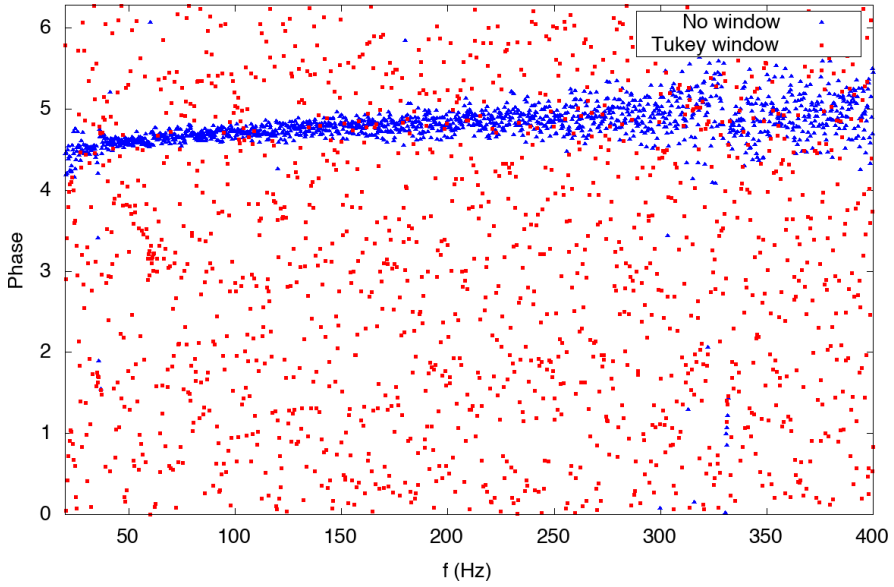
Acknowledgments: LIGO Lab, LIGO Scientific Collaboration, Virgo, US National Science Foundation

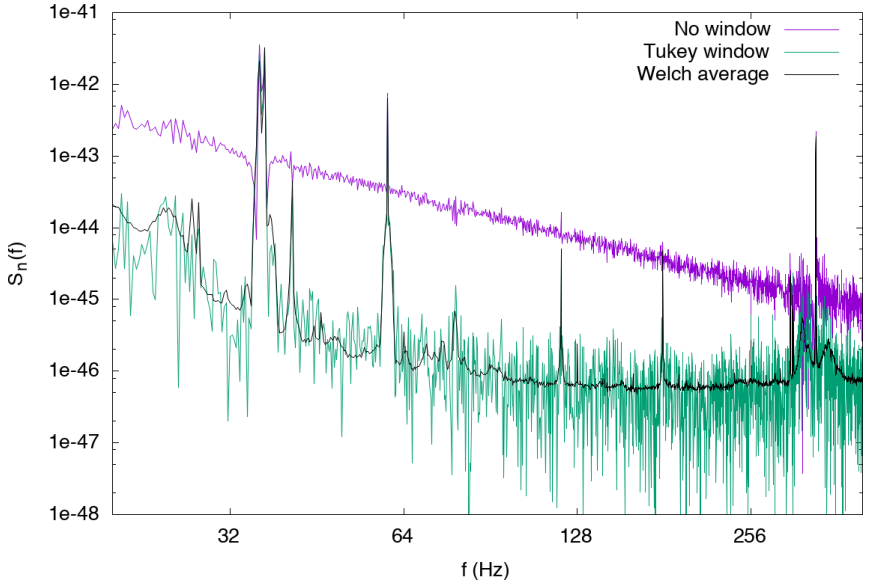
Niels Bohr Group Analysis

1. Phase correlations in LIGO data
2. Correlated residuals in the noise after subtracting signals
3. Non-Gaussianity and non-Stationarity of noise not accounted for in detection confidence
4. Non-Gaussianity and non-Stationarity of noise not accounted for in parameter estimation

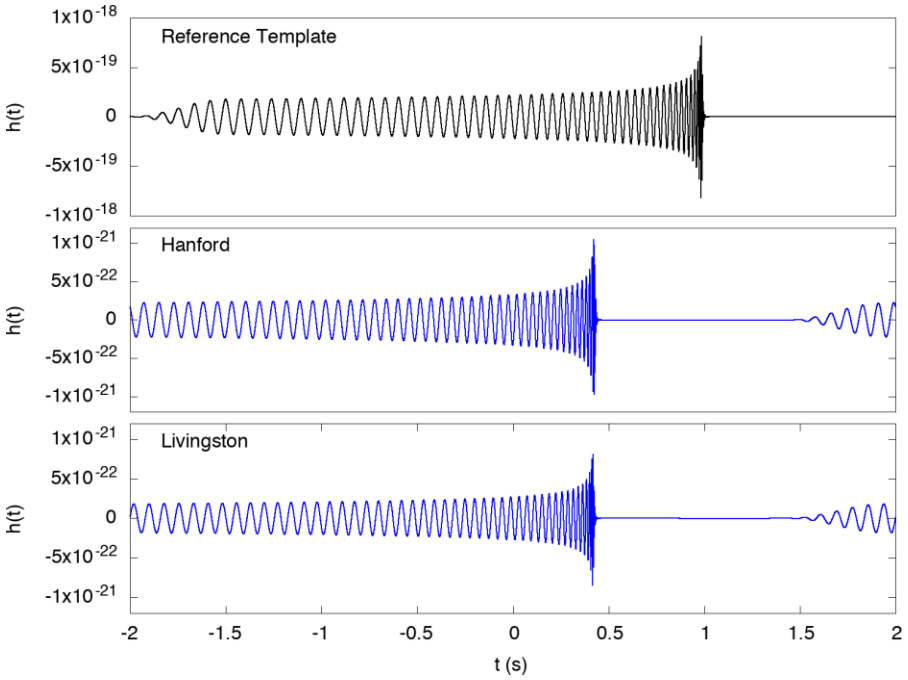
Claim 1: Phase correlations in LIGO data

- The NBI group did not apply a window before performing FFTing the data which results in phase correlations and spectral leakage
- LIGO analyses employ standard data conditioning steps (windows, filters) that prevent phase correlations and leakage



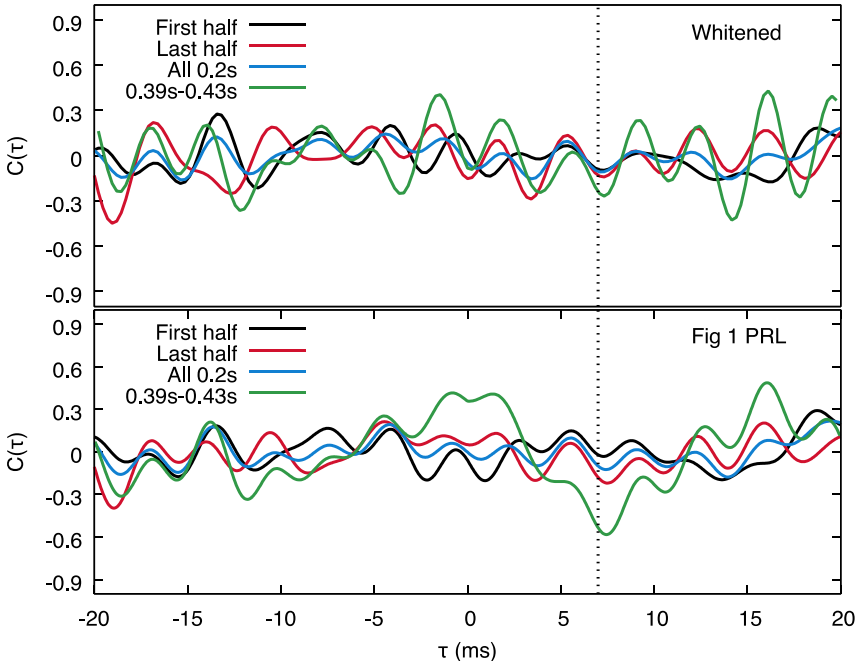


Claim 2: Correlated Residuals



The LIGO Open Data Center provides reference templates for each detection. These are scaled, and time/phase shifted to give e.g. the maximum likelihood solution (shown here for GW150914). Note the H-L phase difference here is 156 degrees and not 180 degrees (i.e. not a sign flip)

File used: GW150914_4_template.hdf5 from: https://www.gw-openscience.org/static/events/LOSC_Event_tutorial.zip

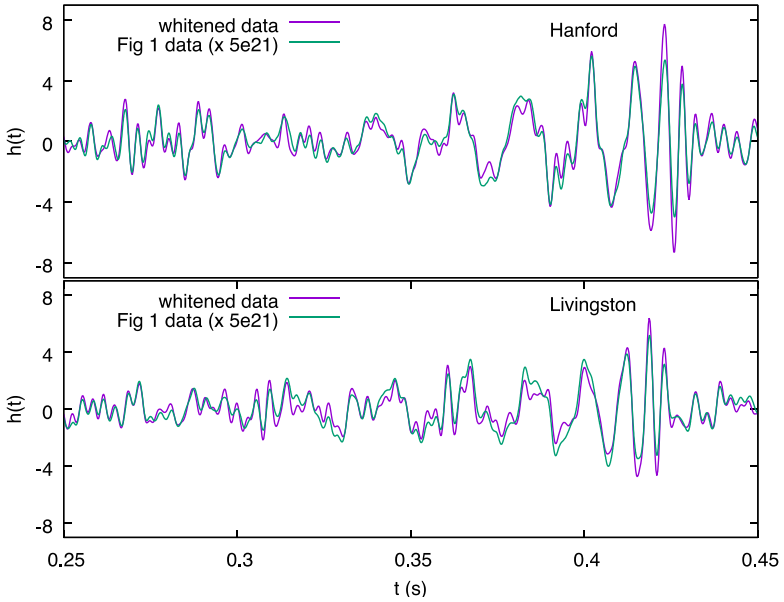


The residuals shown in Figure 1 of the PRL discovery paper used waveforms from the full analysis but applied a different subtraction procedure. A small correlation in the Hanford-Livingston residuals can be seen at the 7 ms GW time delay when computed using a narrow window around merger (green).

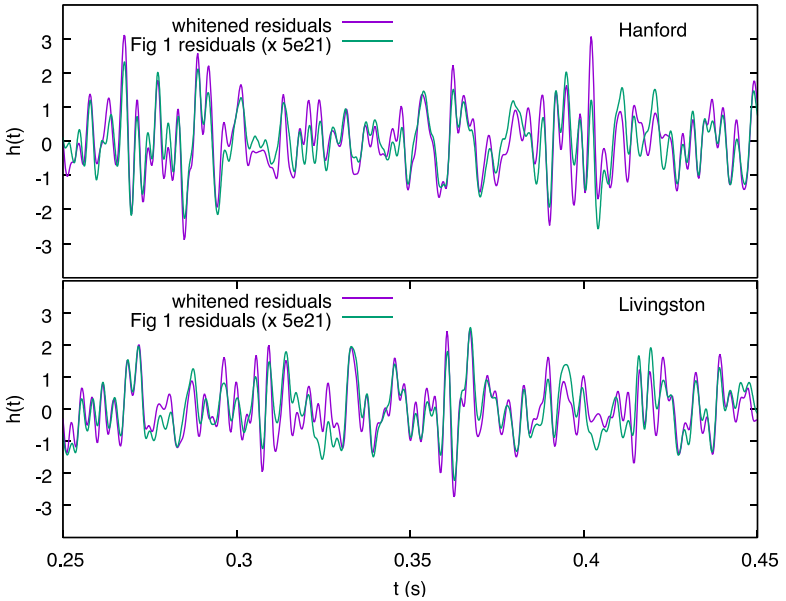
The correlation seen in the Fig 1 data is not statistically significant, and goes away when the signal subtraction is done using the techniques employed in the full analysis

Claim 2: Correlated Residuals (II)

The main difference between the results shown Figure 1 of the discovery paper and the results from the LIGO analysis pipelines is that Figure 1 used a bandpass, notched filter to suppress noise and highlight the signal, while the the analyses use a whitening filter (dividing the data by an estimate of the amplitude spectral density of the noise). This leads to some subtle differences.



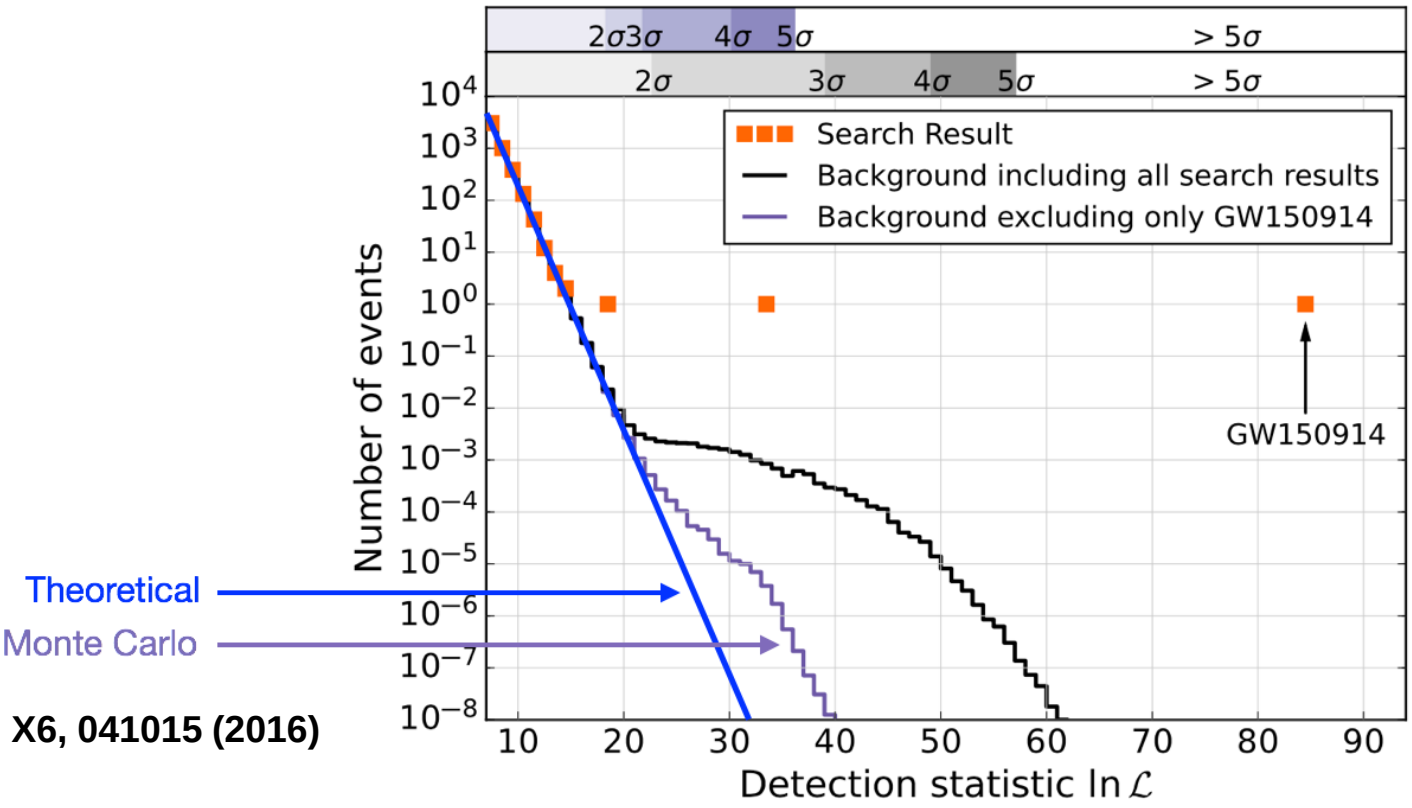
Whitened vs bandpass/notched filtered data



Whitened vs bandpass/notched filtered residuals

Claim 3: Noise properties not accounted for in detection

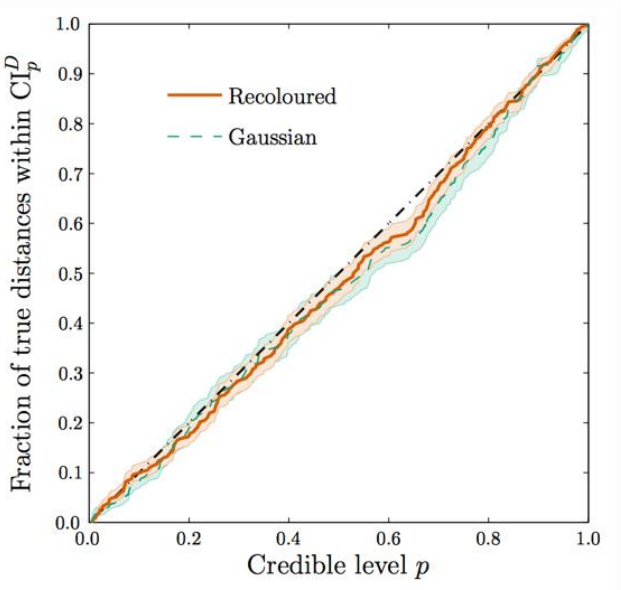
The LIGO data is (mildly) non-stationary and non-gaussian. The LIGO analyses do account for this using Monte Carlo simulations with time-shifted data to measure the false alarm rate as a function of detection statistic



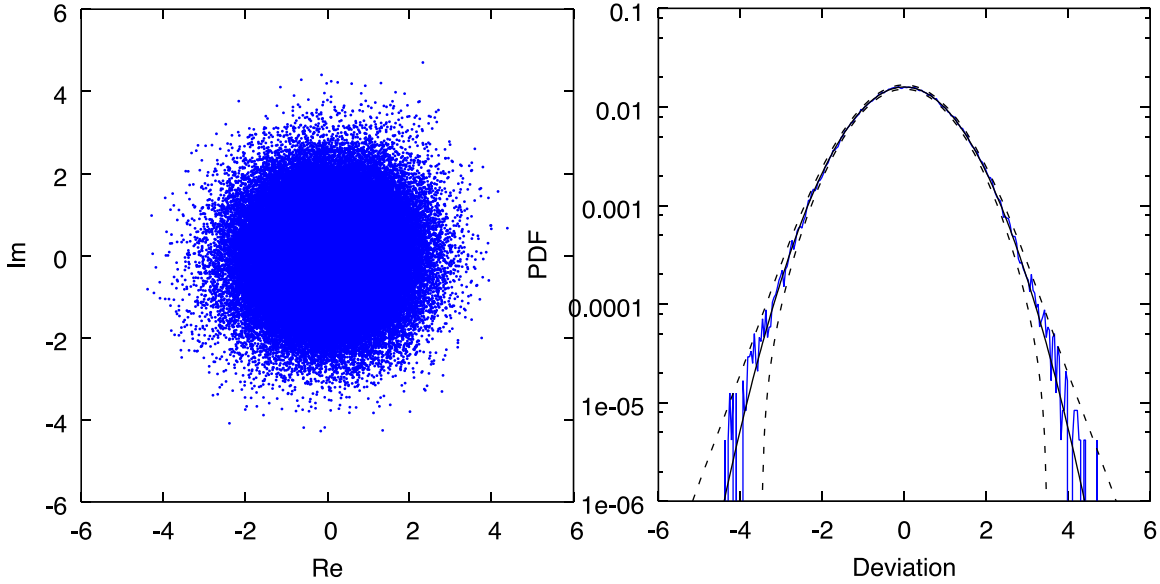
Phys. Rev. X6, 041015 (2016)

Claim 4: Noise properties not accounted for in parameter estimation

The LIGO parameter estimation does use a likelihood function that assumes the noise is stationary and Gaussian. But many checks are applied to make sure this approximation is satisfied. Main checks are injection/recovery studies and checks that the residuals are Gaussian.



Check that injected parameters are recovered in the correct confidence interval



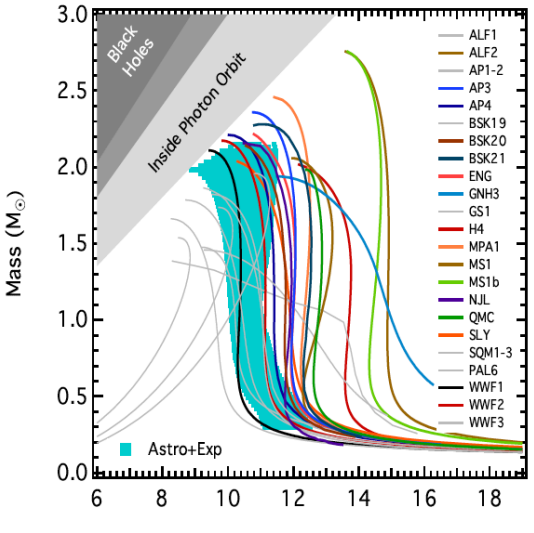
Check that Fourier components of residuals are Gaussian distributed

Constraining the Neutron Star Equation of State with GW170817

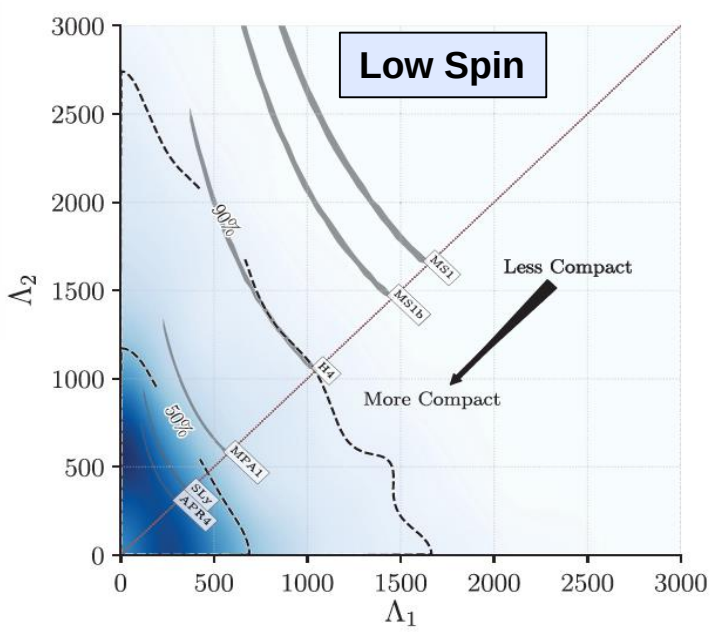
- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

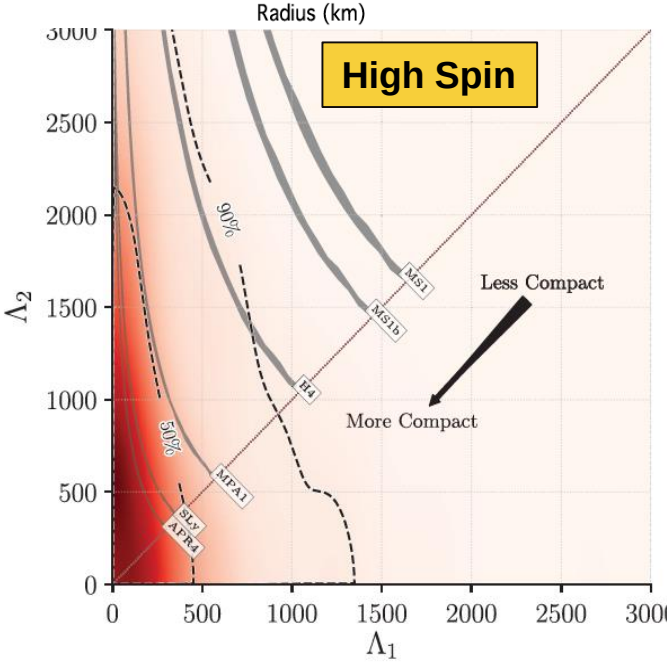
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

- GW170817 data consistent with softer EOS → more compact NS



Ozel and Friere (2016)

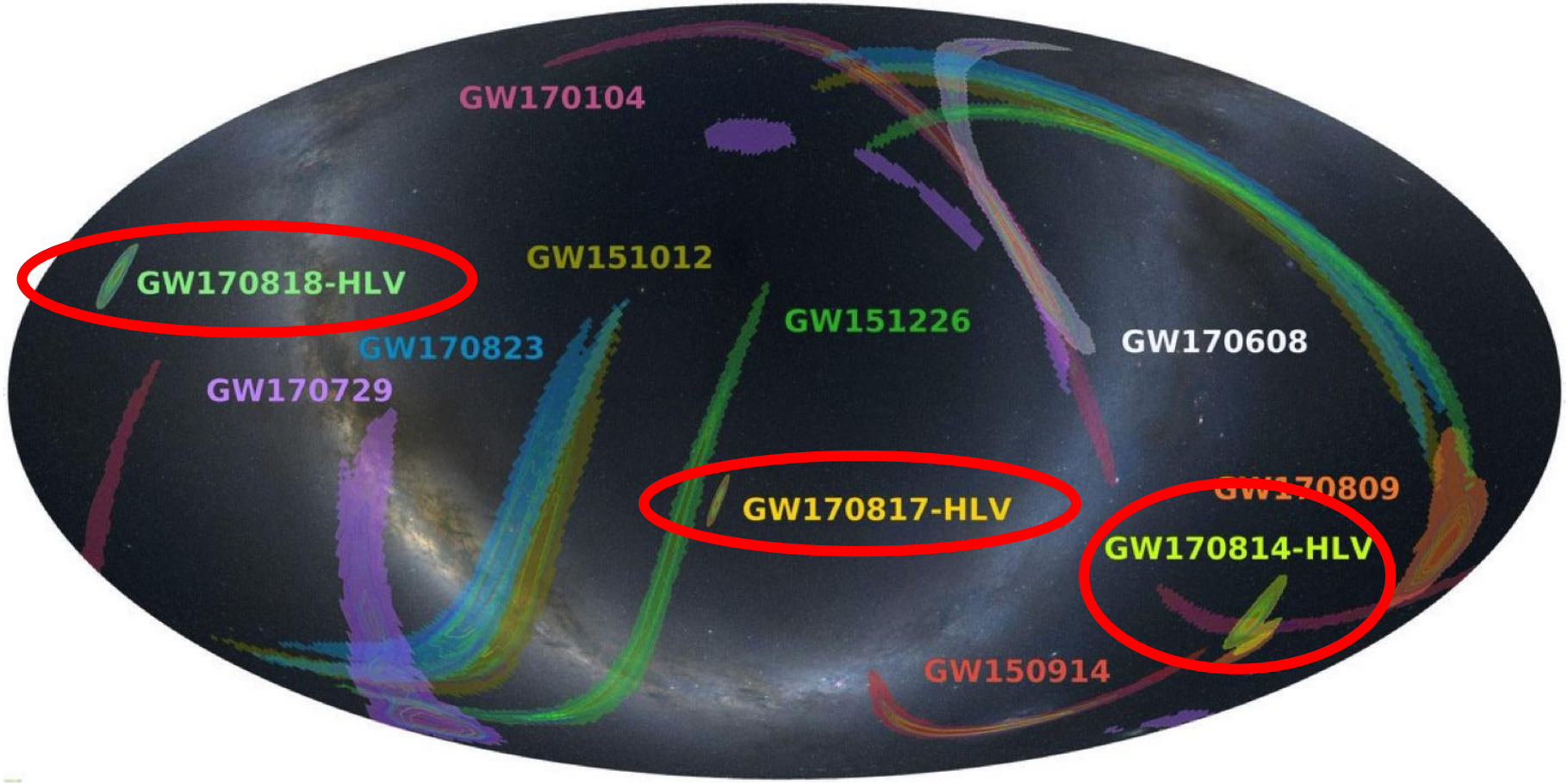




Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)

Skymaps of LIGO-Virgo's Detections

Abbott, et al, (LIGO Virgo Collaboration "Low-Latency Gravitational Wave Alerts for Multi-Messenger Astronomy During the Second Advanced LIGO and Virgo Observing Run", https://arxiv.org/abs/1901.03310



Earth
Space
LIGO Hanford
Virgo
LIGO Livingston